This is a repository copy of *Reference strength values to design against static and fatigue loading polylactide additively manufactured with in-fill level equal to 100%*.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/142395/

Version: Accepted Version

Article:

Ezeh, O.H. and Susmel, L. orcid.org/0000-0001-7753-9176 (2019) Reference strength values to design against static and fatigue loading polylactide additively manufactured with in-fill level equal to 100%. Material Design & Processing Communications, 1 (4). e45. ISSN 2577-6576

https://doi.org/10.1002/mdp2.45

© 2019 John Wiley & Sons, Ltd. This is an author produced version of a paper subsequently published in Material Design & Processing Communications. Uploaded in accordance with the publisher's self-archiving policy.

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Reference strength values to design against static and fatigue loading polylactide additively manufactured with in-fill level equal to 100%

O. H. Ezeh and L. Susmel
Department of Civil and Structural Engineering, The University of Sheffield, Mappin Street, Sheffield, S1 3JD, United Kingdom

Abstract. The aim of this paper is to provide a quantitative examination of the state-of-the-art knowledge of the static and fatigue behaviour of additively manufactured (AM) polylactide (PLA). To this end, existing literature was reviewed and a number of data sets were extracted and re-analysed in terms of static strength and standard S-N curves. Printing direction appears to have little effect on the mechanical behaviour of AM PLA, therefore stress/strain analysis can be performed effectively by simply treating this polymer as a linear-elastic, homogenous, and isotropic material. If static strength cannot be determined experimentally, a conservative reference value of 22 MPa is suggested as being used in situations of practical interest. As far as fatigue is concerned, findings from post-processing reveal that non-zero mean stresses can be modelled by simply using the maximum stress in the cycle. According to the statistical re-analysis discussed in the paper, a reference fatigue curve for the design of AM PLA subjected to uniaxial cyclic loading (for a probability of survival larger than 95%) can be defined by taking the negative inverse slope equal 5.5 and the endurance limit (at $2 \cdot 10^6$ cycles to failure) equal to 10% of the material ultimate tensile strength.

Keywords: additive manufacturing, polylactide (PLA), static assessment, fatigue assessment

Nomenclature

k	negative inverse slope
N_f	number of cycles to failure
N_{Ref}	reference number of cycles to failure ($N_{Ref}=2 \cdot 10^6$ cycles to failure)
P_S	probability of survival
R	stress ratio ($R=\sigma_{min}/\sigma_{max}$)
S_D	standard deviation
T_σ	scatter ratio of the endurance limit, σ_{max}, for 90% and 10% probabilities of survival
θ_R	raster angle
σ_{max}	maximum stress in the fatigue cycle
$\sigma_{MAX,99\%}$	endurance limit at N_{Ref} cycles to failure in terms of σ_{max}
σ_{min}	minimum stress in the fatigue cycle
σ_{UTS}	ultimate tensile strength

1. Introduction

Additive manufacturing (AM) can be described as a collection of technologies that build three-dimensional objects by systematically adding layer-upon-layer of material. Once a virtual model is produced using a 3D-modelling software, the AM machine reads the data from the file and lays down successive layers of materials to create the three-dimensional solid. This technology facilitates the ease and rapid production of objects with complex geometries that would be more difficult and labour consuming for traditional subtractive manufacturing processes. Industry 4.0 is anticipated to be revolutionised in one aspect by the adoption of various AM technologies which process a continuously expanding range of material types from classic polymers, metals, composites, to more novel ones.

Polymers are by far the most used class of materials for AM processes, so that several commercial 3D-printers exist that can be used for acrylonitrile butadiene styrene (ABS) or PLA fabrication. In terms of technological process, polymers are additively manufactured by melting/extruding either powders, wires or flat sheets. PLA is a biodegradable/biocompatible thermoplastic aliphatic polyester which is widely used for tool jigs, fixtures, and in biomedical applications to make devices such as vascular stents.

To gain more confidence in deploying PLA structures made from AM processes into the industrial scene whether as parts of automotive, aircraft or biomedical devices, care must be taken to mitigate against static and fatigue failure.

In this scenario, this paper aims to review the state of the art knowledge of the mechanical strength of AM PLA to give quantitative recommendations to safely perform static and fatigue assessment in situations of practical interest.

2. Static strength of 3D-printed PLA

PLA is a polymer that is derived from renewable sources such as corn starch, cassava roots, chips, or sugarcane. It can easily be processed on standard manufacturing equipment to yield moulded parts, films or fibres[1]. It is one of the few polymers in which its stereo-chemical structure can be modified straightforwardly by polymerising a controlled mixture of the L- or D-isomers to yield high molecular weight amorphous or crystalline chemical systems. The mechanical properties and crystallisation behaviour of PLA is very dependent on the molecular weight and morphology. Crystallized process conditions produce PLA with significantly higher tensile strength and stiffness than amorphous ones.

Whilst AM is conceived as a simple and innovative way to process PLA, machine settings in the form of process parameters have been considered by experimental evaluations to study consequential effects on the material mechanical behaviour. The structural response of AM PLA under static loading[2-5] is affected by the following parameters: layer thickness, infill percentage, nozzle size, manufacturing orientation (Fig. 1), filling pattern, filling rate and fill temperature. Important manufacturing variables that affect printing resolution and integrity include the shell thickness which is recommended to be set to a value equal to a multiple of the nozzle diameter to effectively reduce, in the bulk material, the formation of manufacturing voids and defects[4].

As to the static behaviour of AM components of PLA, the material ultimate tensile strength and Young's modulus tend to decrease both as the infill angle increases and as the thickness of the shell decreases[6]. Static strength also depends on the thickness of the manufacturing layers[7]. In terms of stress-strain response, the mechanical behaviour of AM PLA is seen to be mostly brittle with levels of ductility varying as the printing direction changes[3, 8, 9]. This can be due to discrepancies between internal cohesion forces among the polymer chains and inter-layer forces which account for the cohesion of the whole work piece. AM PLA is seen to exhibit a strong tension/compression asymmetry and is strain rate-sensitive[8].

Even if, strictly speaking, raster orientation and shell thickness somehow affect the overall mechanical behaviour of AM PLA, much experimental evidence suggests that, from an engineering design viewpoint, the influence of these parameters on elastic modulus, ultimate tensile strength, σ_{UTS}, and yield stress can be neglected with little loss of accuracy[4]. The validity of this engineering simplification is clearly proven by the diagram of Fig. 2a that summarises the results generated by Ahmed and Susmel[4] by testing specimens not only manufactured by making the raster angle, θ_R, vary in the range 0˚-90˚, but also setting the shell thickness, t_s, equal to 0, 0.4 and 0.8 mm. In the present investigation θ_R is defined as the angle between the reference printing direction and the longitudinal axis of the specimens themselves (Fig. 1). The diagram of Fig. 2a makes it evident that both angle θ_R and shell thickness t_s had little influence on σ_{UTS}, with all the data being within two standard deviations, S_D, of the mean. This tells us for a direct CAD to FEA design inter-operability, where AM PLA can be treated as a homogenous and isotropic material[4, 5].

The chart of Fig. 2b summarises the static strength for different values of raster angle $\theta_{R,}$ with these experimental results being taken from the technical literature[4, 7-13]. According to this diagram, by making the key manufacturing parameters vary in their ranges of interest, the resulting material ultimate tensile strength is seen to span between 30 MPa and 90 MPa, with these values being similar to those characterising PLA made via traditional methods such as, for instance, injection moulding[2]. As per the chart of Fig. 2b, the average value of θ_{UTS} is equal to 55 MPa and the standard deviation to 16.6 MPa. Therefore, when the static strength of the AM PLA being designed cannot be determined by running appropriate experiments, a reference value of 38.5 MPa can be used to perform the static assessment by referring to one standard deviation of the mean. In contrast, in those situations in which the level of conservatism needs to be increased, the design static strength can be taken equal to 22 MPa, i.e., equal to the value that is obtained by subtracting two standard deviations from the mean (Fig. 2b). To conclude, it is worth observing that the high level of scattering characterising the results summarised in Fig. 2b can simply be ascribed to the fact that these strength values were generated by testing specimens additively manufactured not only from parent materials commercialised by different suppliers, but also by using different 3D-printers and different values for the key technological variables.

3. Fatigue strength of AM PLA

Considering fatigue behaviour, experiments conducted by Letcher and Waytashek[9] as well as by Afrose et al.[12] relay insights that, as expected, mechanical behaviour is direction dependent (i.e., anisotropic). Further, detailed experimental investigations by Jerez-Mesa et al.[14] demonstrates that layer height, nozzle diameter, fill density and printing speed affect the overall fatigue strength in a complex way with mutual interactions being difficult to be assessed and quantified without performing time consuming and costly experimental trials. In particular, according to their experimental investigation and subsequent post-processing the fatigue strength of the AM polymer being tested reached its maximum for a fill density of 75% and not of 100% as one would expect.

Letcher and Waytashek[9] tested under fully-reversed (R=-1) axial fatigue loading a large number of specimens that were manufactured flat on the build plate by using commercial 3D-printer "Makerbot Replicator 2x". These dog-bone samples with 13mm x 6mm rectangular cross-section were manufactured by setting angle θ_R equal to 0°, 45° and 90°. The fatigue tests were run using sinusoidal load signals with frequency equal to 2 Hz up to 10^3 cycles, to 5 Hz up to 10^4 cycles, and, finally, to 20 Hz until complete breakage took place.

Afrose et al.[12] employed 3D printer "Cube-2" to make flat specimens having net width and thickness equal to 10mm and to 4mm, respectively. For this experimental investigation as well, the specimens being tested were manufactured flat on the build plate by setting the raster angle equal to 0°, 45° and 90°. Finally, fatigue failures were generated in the low-cycle fatigue regime under a load ratio, R, invariably equal to zero at a frequency of 1 Hz.

The experimental results extracted from the technical articles[9, 12] mentioned above are summarised all together in the S-N diagram of Figure 3. In particular, this log-log chart was built by plotting the ratio between the maximum stress in the fatigue cycle, σ_{max}, and σ_{UTS} versus the number of cycles to failure, N_f. In this diagram σ_{max} is used to take into account in a very simple and direct way the effect of non-zero mean stresses[15-17].

The scatter band of Fig. 3 (determined by referring to a probability of survival, P_S, equal to 99% and 1%) was calculated by post-processing the experimental results under the hypothesis of a log-normal distribution of the number of cycles to failure for each stress level, with the confidence level being taken equal to 95%[18]. In Fig. 3 the results from the statistical analysis are reported in terms of negative inverse slope, k, endurance limit, $\sigma_{MAX,99\%}$, at

$N_{Ref}=2\cdot10^6$ cycles to failure for $P_S=99\%$, and, finally, scatter ratio, T_σ, of the endurance limit for $P_S=90\%$ and $P_S=10\%$.
The S-N diagram of Fig. 3 shows that both raster angle θ_R and load ratio $R=\sigma_{min}/\sigma_{max}$ just marginally affected the fatigue data scattering ($T_\sigma=1.596$), with the fatigue strength of 3D-printed PLA being directly related to the static strength.
By bearing in mind the physiological scattering that accompanies fatigue data, the S-N chart of Fig. 3 strongly supports the idea that AM PLA can accurately be designed again fatigue by simply regarding this material as homogenous and isotropic.
It is possible to conclude the present section by observing that, as per the statistical re-analysis which is summarised in the S-N diagram of Fig. 3, a reference design fatigue curve (for $P_S\geq95\%$) suitable for performing the fatigue assessment of AM PLA with infill level equal to 100% can be taken as follows[15]:

$$k=5.5 \quad (1)$$

$$\sigma_{MAX}=0.1\cdot\sigma_{UTS} \quad \text{at } N_{Ref}=2\cdot10^6 \text{ cycles to failure} \quad (2)$$

4. Conclusions

After post-processing a number of experimental data taken from the technical literature and generated by testing un-notched flat specimens, the static and fatigue behaviour of AM PLA was studied by evaluating the effect of different manufacturing variables.
Findings from this investigation can be summarized as follows:

- static and fatigue strength of AM PLA is seen to be slightly affected by raster orientation;
- since the effect of the AM filament orientation on the mechanical behaviour of AM PLA can be neglected with little loss of accuracy, for design purposes, AM PLA can be treated as a homogenous and isotropic material;
- when appropriate experiments cannot be run to determine it rigorously, σ_{UTS} can be taken equal to 38.5 MPa or to 22 MPa to perform the static assessment by referring to one or two standard deviations of the mean, respectively;
- the mean stress effect in fatigue of AM PLA can be assessed in terms of maximum stress in the cycle;
- when a specific fatigue curve cannot be determined experimentally, components of AM PLA can be designed against fatigue (for $P_S\geq95\%$) by using a reference design curve with negative inverse slope k equal to 5.5 and endurance limit (extrapolated at $N_{Ref}=2\cdot10^6$ cycles to failure) equal to $0.1\cdot\sigma_{UTS}$.

- More systematic work needs to be done to study the effects of individual and combined process parameters on the mechanical behaviour of un-notched and notched AM PLA.

References

1. Kaplan D. Introduction to biopolymers from renewable resources. In: Kaplan D, eds. Biopolymers from Renewable Resources. Berlin: Springer; 1998: 1-29.

2. Ahmed AA, Susmel L. Additively Manufactured PLA under static loading: strength/cracking behaviour vs. deposition angle. Procedia Struct Integrity. 2017;3:498-507.

3. Ahmed, A. A., Susmel, L. On the use of length scale parameters to assess the static strength of notched 3D-printed PLA. Frattura ed Integrità Strutturale Vol. 11, Issue 41, pp. 252-259, 2017.

4. Ahmed AA, Susmel L. A material length scale–based methodology to assess static strength of notched additively manufactured polylactide (PLA). Fatigue Fract Eng Mater Struct. 2018;41:2071-2098.

5. Ahmed AA, Susmel L. Static assessment of plain/notched polylactide (PLA) 3D-printed with different infill levels: Equivalent homogenised material concept and Theory of Critical Distances. Fatigue Fract Eng Mater Struct. 2018;1–22. https://doi.org/10.1111/ffe.1295822.

6. Lanzotti A, Grasso M, Staiano G, Martorelli M. The impact of process parameters on mechanical properties of parts fabricated in PLA with an open-source 3-D printer. Rapid Prototyp J. 2015;21(5):604-617.

7. Chacón JM, Caminero MA, García-Plaza E, Núñez PJ. Additive manufacturing of PLA structures using fused deposition model-ling: effect of process parameters on mechanical properties and their optimal selection. Mater Des. 2017;124:143-157.

8. Song Y, Li Y, Song W, Yee K, Lee K-Y, Tagarielli VL. Measurements of the mechanical response of unidirectional 3D-printedPLA. Mater Des. 2017;123:154-164.

9. Letcher T, Waytashek M. Material property testing of 3D-printed specimen in PLA on an entry-level 3D-printer. In: Proceedings of the ASME 2014 International Mechanical Engineering Congress & Exposition (IMECE2014), 14–20 November 2014, Montreal, Quebec, Canada, IMECE2014–39379.

10. Ferreira RTL, Amatte IC, Dutra TA, Bürger D. Experimental characterization and micrography of 3D printed PLA and PLA reinforced with short carbon fibers. Composites Part B. 2017;124:88-100.

11. Raja SA, Muthukumaran E, Jayakrishna K. A Case Study of 3D Printed PLA and Its Mechanical Properties. Materials Today: Proceedings. 2018;5:11219–11226.

12. Afrose F, Masood SH, Iovenitti P, Nikzad M, Sbarski I. Effects of part build orientations on fatigue behaviour of FDM-processed PLA material. Prog Addit Manuf. 1;2016:21-28.

13. Ezeh OH, Susmel L. Designing additively manufacture notched PLA against static loading. In: Proceedings of International Symposium on Notch Fracture, Edited by S. Cicero et al., 29-31 March 2017, Santander, Spain, ISBN: 978-84-617-9611-3.

14. Jerez-Mesa R, Travieso-Rodriguez JA, Llumà-Fuentes J, Gomez-Gras G, Puig D. Fatigue lifespan study of PLA parts obtained by additive manufacturing. Procedia Manuf. 13;2017:872-879.

15. Ezeh OH, Susmel L. On the fatigue strength of 3D-printed polylactide (PLA). Procedia Structural Integrity. 2018;9:29-36.

16. Socie DF. Multiaxial Fatigue Damage Models. Tran ASME, J Eng Mater Technol. 1987;109(4):293-298.

17. Jadallah O, Bagni C, Askes H, Susmel L. Microstructural length scale parameters to model the high-cycle fatigue behaviour of notched plain concrete. Int J Fatigue. 2016;82:708-720.

18. Al Zamzami I, Susmel L. On the accuracy of nominal, structural, and local stress-based approaches in designing aluminium welded joints against fatigue. Int J Fatigue. 2017;101:137-158.

List of Figures

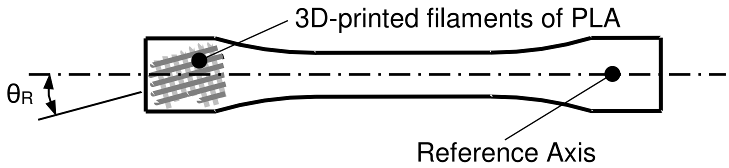

Figure 1. *Definition of raster angle θ_R.*

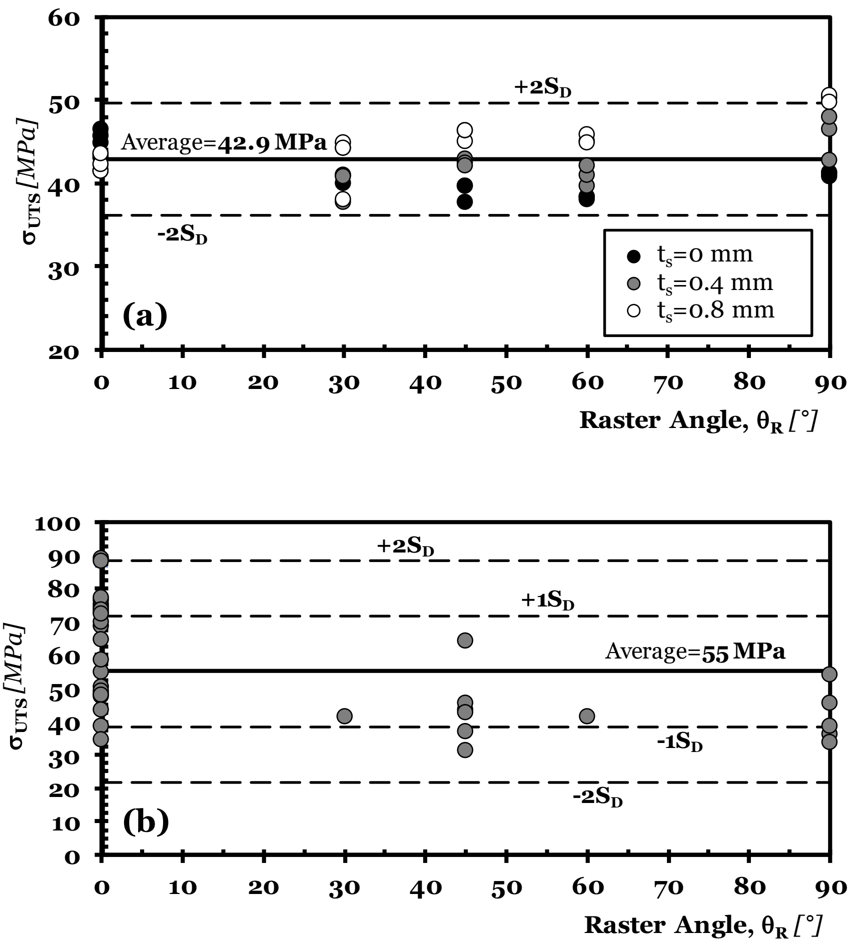

Figure 2. *Tensile strength experimentally determined by Ahmed and Susmel*[4] *by testing specimens manufactured with raster angle, θ_R, varying in the range 0°-90° and shell thickness, t_s, in the range 0-0.8 mm (a); ultimate tensile strength for different values of raster angle, θ_R, experimentally determined by testing under tensile loading specimens of AM PLA.*[4, 7-13] *(b).*

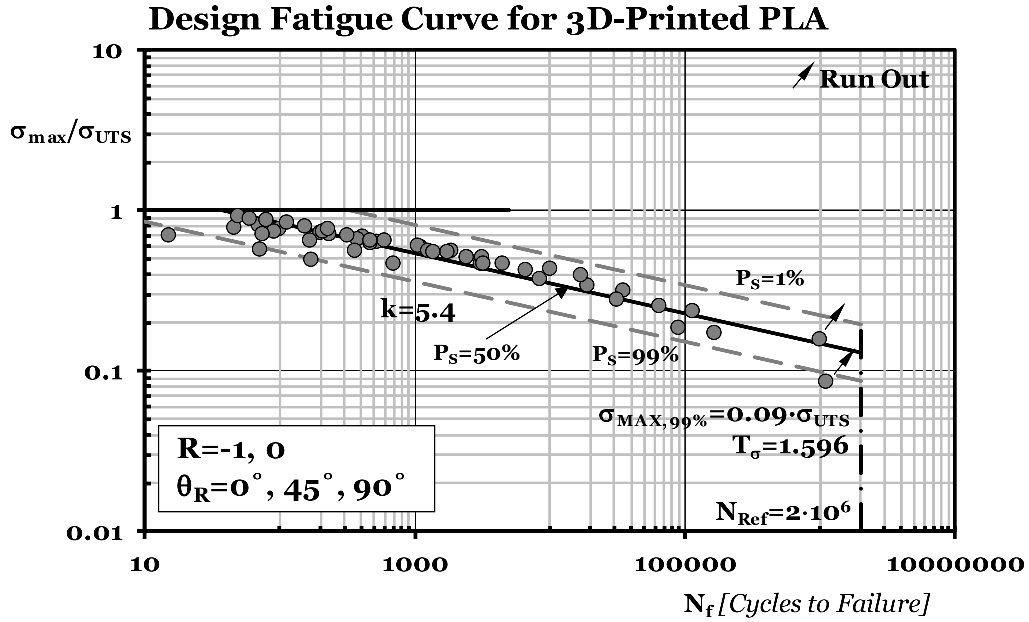

Figure 3. *Design fatigue curve for 3D-Printed PLA obtained by post-processing the fatigue results generated by Letcher and Waytashek[9] under R=-1 together with those generated by Afrose et al.[12] under R=0.*