Proceedings Paper:

Susmel, L. orcid.org/0000-0001-7753-9176 (2021) Fatigue assessment of additively manufactured plain and notched polylactide (PLA). In: Akid, R., Berto, F., Cawte, E.R., Charhardehi, A., Irving, P., Roberts, P., Whittaker, M.T. and Yates, J.R., (eds.) Proceedings of the 8th Engineering Integrity Society International Conference on Durability & Fatigue. Fatigue 2021 - The 8th Engineering Integrity Society International Conference on Durability & Fatigue, 29-31 Mar 2021, Virtual conference. Engineering Integrity Society . ISBN 978-0-9544368-5-8

FATIGUE ASSESSMENT OF ADDITIVELY MANUFACTURED PLAIN AND NOTCHED POLYLACTIDE (PLA)

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The present paper investigates the influence of raster orientation as well as of non-zero mean stresses on the fatigue behaviour of additively manufactured plain and notched polylactide (PLA). PLA is a biodegradable polymer that can be 3D-printed easily and at a relatively low cost. The Theory of Critical Distances (TCD) is the name which has been given to a group of fatigue assessment techniques that are all based on the use of a material critical distance. The accuracy and reliability of the TCD in estimating the fatigue lifetime of additively manufactured PLA is assessed against numerous experimental results generated by testing notched specimens containing different geometrical features. The TCD is seen to be highly accurate. This demonstrates that this design approach can be used successfully to design against fatigue also notched components of 3D-printed PLA.

INTRODUCTION

By its nature, Additive Manufacturing (AM) allows complex forms to be incorporated into components suitable for being used in advanced structural applications. According to ASTM F42, AM is *"the process of joining materials to make objects from 3D-model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies"*. Accordingly, AM is an "additive" process which can be more effective than traditional "subtractive" manufacturing technologies. This holds true especially in the presence of complex geometries that would be difficult to be fabricated via traditional manufacturing processes.

As far as polymers are concerned, certainly acrylonitrile butadiene styrene (ABS) and polylactide (PLA) are the most common materials that are used along with AM technologies. Polymers can be additively manufactured by making use of powders, wires and flat sheets that are melted using a variety of different techniques, with fusion deposition modelling being the most popular technology that is employed in off-the-shelf 3D-printers. PLA is a biodegradable, absorbable and biocompatible polymer that is widely adopted to manufacture components having complex shape to be used in biomedical, automotive and mechanical applications.

As mentioned earlier, one of the most relevant peculiarities of AM is that components having complex forms can be manufactured by reaching a very high level of accuracy in terms of both shape and dimensions. As far as the design problem is concerned, the fact that 3D-printed components can contain very complex geometrical features results in localised stress concentration

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phenomena, with stress raisers reducing markedly the fatigue strength of the components themselves. Therefore, reliable and straightforward design methodologies are needed to perform the fatigue assessment of additively manufactured (AM) materials accurately.

In this context, certainly the Theory of Critical Distances (TCD) is the most powerful candidate to be employed systematically in industry to design AM components against fatigue because:

- it is successful independently of shape and sharpness of the notch being designed;
- it models the material morphology by using a suitable critical distance to calculate the design stress;
- the relevant stress fields can be determined by modelling the mechanical behaviour of the material under investigation by adopting a simple linear-elastic constitutive law;
- the design stress can be determined by post-processing the results from standard linear-elastic Finite Element (FE) models, with the same numerical solid models being used to inform also the manufacturing process.

In this scenario, the present paper reviews the research work we have supervised over the last 5 years [1-6] in order to devise a robust methodology suitable for performing the fatigue assessment of plain and notched 3D-printed PLA.

EXPERIMENTAL DETAILS

By using New Verbatim filaments of white PLA with initial diameter of 2.85mm, a large number of plain and notched specimens were additively manufactured via 3D-printer Ultimaker 2 Extended+. The values of the adopted manufacturing parameters were as follows [1, 4, 5]: nozzle size=0.4 mm, nozzle temperature=240ºC, build-plate temperature=60ºC, layer height=0.1 mm, shell thickness=0.4 mm, fill density=100%, and print speed=30 mm/s. As per Fig. 1, the samples being tested were manufactured flat on the build-plate by making angle θ_p vary in the range 0º-90º. In particular, while the extruded filaments were deposited, layer upon layer, always at ±45° to the y_p axis (Fig. 1), the angle between the longitudinal axis of the specimens and axis y_p was varied so that specimens characterised by different deposition lay-ups could be manufactured (see Fig. 1).

The samples being tested under both static and fatigue loading had thickness in the range 3-5 mm. The un-notched specimens used to run the static tests had width equal to 15 mm [1], whereas those used to investigate the fatigue behaviour of AM PLA had width equal to 6 mm [4].

The notched specimens being manufactured [5] had all net width equal to 6 mm, gross width to 25 mm. The bluntly U-notched specimens had root radius, r_n, equal to 3 mm, whereas the intermediate U-notched specimens had r_n=1 mm. Finally, the sharply V-notched specimens had notch opening angle equal to 35° and r_n=0.15 mm.

By setting the displacement rate equal to 2 mm/min, a number of plain specimens were tested under quasi-static tensile loading by using a Shimadzu universal machine. In these un-notched samples, the local strains were measured systematically during testing through an axial extensometer having gauge length equal to 50 mm [1].

The fatigue tests [4, 5] were run by using an electric fatigue table. Both the plain and notched specimens were tested under sinusoidal axial loading, with the magnitude of the applied axial force being gathered continuously during testing through an axial loading cell. Since the critical cross-sectional area of the specimens was very small, the fatigue tests were run up to the complete breakage of the samples themselves. All the experiments were run at a frequency of 10 Hz. The nominal load ratio, $R=F_{min}/F_{max}$, was set not only equal to -1 (fully-reversed loading), but also larger than -1. The latter loading paths were used to investigate the effect of non-zero mean stresses on the overall fatigue strength of plain/notched 3D-printed PLA. The run-out tests were all stopped at $2 \cdot 10^6$ cycles to failure.

MECHANICAL BEHAVIOUR

The stress vs. strain charts seen in Fig. 2 show the mechanical behaviour as measured under static loading by testing the un-notched specimens with net width equal to 15 mm. These diagrams make it evident that the stress vs. strain behaviour of the AM material being investigated was characterised by a response that was predominantly linear up to the maximum value of the stress being recorded during testing. According to this experimental evidence, the hypothesis can be formed that the mechanical behaviour of the tested AM PLA can be modelled effectively via a simple linear-elastic constitutive, with this simplification resulting just in a little loss of accuracy.

The charts reported in Fig. 3 summarise the influence of manufacturing angle θ_p on the ultimate tensile strength, σ_{UTS}, the 0.2% proof stress, $\sigma_{0.2\%}$, and Young's modulus, E (see Fig. 1 for the definition of manufacturing angle θ_p). In terms of reference mechanical properties, the results generated by testing the plain samples returned the following average values: E equal to 3479 MPa, $\sigma_{0.2\%}$, equal to 41.7 MPa and σ_{UTS} equal to 42.9 MPa. The diagrams of Fig. 3 make it evident that the infill direction had little effect on the overall mechanical behaviour of the AM material being investigated. In particular, the experimental results expressed in terms of σ_{UTS}, $\sigma_{0.2\%}$ and E in Fig. 3 are seen to be all within two standard deviations, S_D, of the mean. Accordingly, the hypothesis can be formed that the 3D-printed PLA under investigation behaves like a homogenous and isotropic material, with this holding true as long as AM objects are manufactured flat on the build-plate.

FATIGUE BEHAVIOUR OF UN-NOTCHED PLA

As far as fatigue assessment is concerned, much experimental evidence [3, 4] suggests that the design problem can be simplified greatly by observing that the maximum stress in the cycle, σ_{max}, is successful in taking into account the detrimental effect of non-zero mean stresses.

Further, as mentioned briefly in the previous section, the manufacturing direction is seen to have little influence on the mechanical behaviour of AM PLA, with this holding true as long as objects are 3D-printed flat on the build plate.

According to these two simplifying hypotheses, if the effect of the raster angle is disregarded and fatigue damage is quantified in terms of σ_{max}, fatigue assessment can then be performed by directly using the unifying scatter band plotted in the SN chart of Fig. 4 [3, 4]. This scatter band was built by post processing not only the data we generated in the Structures Laboratory of the University of Sheffield [4], but also other data taken from the literature [7, 8]. Accordingly, the scatter band seen in Fig. 4 was determined using a large number of experimental results that were generated by testing AM PLA fabricated by making the printing direction vary in the range 0°-90°. Further these un-notched specimens with different material lay-ups were tested under load ratios,

$R=\sigma_{min}/\sigma_{max}$, equal to -1, -0.5, 0, and 0.3. In the SN diagram of Fig. 4, N_f is the number of cycles to failure, k is the negative inverse slope, P_S is the probability of survival, $\sigma_{MAX,50\%}$ is the maximum value of the endurance limit extrapolated at $N_{Ref}=2\cdot10^6$ cycles to failure, and T_σ is the scatter ratio of the endurance limit for 90% and 10% probabilities of survival.

The scatter band of Fig. 4 was calculated for P_S equal to 90% and 10% under the hypothesis of a log-normal distribution of the number of cycles to failure for each stress level, with this being done by setting the confidence level invariably equal to 95% [9].

According to the unifying SN curve shown in Fig. 4, whenever it is not possible to determine experimentally the fatigue strength of the specific AM PLA being employed, then fatigue assessment is recommended to be performed (for P_S>90%) by adopting a design curve having negative inverse slope, k, equal to 5.5 and endurance limit, $\sigma_{MAX,Design}$, at $N_{Ref}=2\cdot10^6$ cycles to failure equal to $0.1\cdot\sigma_{UTS}$ [3, 4].

THE TCD TO ESTIMATE FATIGUE LIFETIME OF NOTCHED PLA

The use of the linear-elastic TCD to estimate fatigue lifetime takes as its starting point the assumption that the critical distance value to be used to calculate an effective equivalent stress is a material property whose value increases with decreasing of N_f, i.e. [10, 11]:

$$L = A \cdot N_f^B \tag{1}$$

where, A and B are material fatigue constants to be determined by running appropriate experiments. In this context, it is important to recall that A and B are different for different materials and different load ratios, but their values do not depend on the features of the notch being assessed [10].

If Eq. (1) is assumed to be known for the material being assessed, the TCD can then be formalised in different ways by simply changing the definition of the integration domain used to calculate the maximum value of the effective stress, $\sigma_{eff,max}$.

In particular, if such a stress quantity is estimated according to the Point Method, then $\sigma_{eff,max}$ can be calculated as (Figs 5a and 5b) [10-12]:

$$\sigma_{eff,max} = \sigma_{y,max}\left(\theta = 0°, r = \frac{L(N_f)}{2}\right) \tag{2}$$

Alternatively, $\sigma_{eff,max}$ can also be determined by averaging the maximum value of the linear-elastic stress, $\sigma_{y,max}$, along a line over a distance equal to $2L_M(N_f)$, i.e. (Figs 5a and 5c) [10-12]:

$$\sigma_{eff,max} = \frac{1}{2 \cdot L_M(N_f)} \int_0^{2 \cdot L_M(N_f)} \sigma_{y,max}(\theta = 0°, r) \cdot dr \tag{3}$$

This formalisation of the TCD is known as the Line Method [12].

Lastly, the maximum value of the effective stress can also be calculated by averaging $\sigma_{1,max}$ over a semi-circular area centred at the notch tip and having radius equal to $L_M(N_f)$ [10-12]. Such a form of the TCD is known as the Area Method (AM) and it can be formalised as follows (Figs 5a and 5d):

$$\sigma_{\mathrm{eff,max}} = \frac{4}{\pi L_M^2(N_f)} \int_0^{\frac{\pi}{2}} \int_0^{L_M(N_f)} \sigma_{1,\max}(\theta, r) \cdot r \cdot dr \cdot d\theta \tag{4}$$

Finally, independently of the strategy followed to calculate the the effective stress, the number of cycles to failure can directly be estimated through the Wöhler curve describing the fatigue behaviour of the parent material the component being assessed is made of, that is [10, 11]:

$$N_f = N_{\mathrm{Ref}} \cdot \left(\frac{\sigma_{\mathrm{MAX}}}{\sigma_{\mathrm{eff,max}}}\right)^k \tag{5}$$

With regard to the use of Eqs (2) to (4) to estimate fatigue lifetime of notched components, it is evident that they have to be applied through appropriate recursive procedures [10], since the number of cycles to failure needed to calculate the critical distance value according to Eq. (1) is, obviously, never known a priori.

Turning to the calibration of power law (1), constants A and B can directly be estimated from the un-notched material fatigue curve and from another fatigue curve determined by testing specimens containing a notch having known profile and known sharpness [10, 11]. This way of estimating constants A and B is explained in Fig. 5e. In more detail, according to the Point Method, given a reference number of cycles to failure, N_f^*, it is easy to calculate the distance from the notch tip, $L_M(N_f)/2$, at which the maximum value of the linear-elastic stress, $\sigma_{y,max}$, equals the value of the maximum stress, σ^*_{max}, that has to be applied to the plain material to break it at N_f^* cycles to failure (Fig. 5e). Therefore, the critical distance value can then be determined for all the N_f values from the low- to the high-cycle fatigue regime, allowing constants A and B to be estomated unambiguously.

To apply the TCD to post-process the notch fatigue results we generated in the Sheffield Structures Laboratory [5], the local linear-elastic stress fields were calculated using commercial FE software ANSYS®. As per the simplifying assumptions made in the previous sections, the solutions were calculated by modelling the AM polymer under investigation as a linear-elastic, homogeneous and isotropic material.

Constant A and B in Eq. (1) for the AM PLA being assessed were determined from the experimental plain fatigue curve as calculated in Ref. [4] for P_S=50% (Fig. 4) and the fatigue curve determined by testing the sharply notched specimens with r_n=0.15 mm. The calibration process shown in Fig. 5e applied along with the two calibration fatigue curves mentioned above returned the following L_M vs. N_f relationship:

$$L_M(N_f) = 16.4 \cdot N_f^{-0.242} \ [\mathrm{mm}] \tag{5}$$

This power law was then used to post-process the experimental results being generated according to both the Point and the Area Method. In contrast, the Line Method could not be used because the length of the required integration domain in the medium/low-cycle fatigue regime - i.e., $2L(N_f)$ - was larger than half net-width of the specimens [12].

The fatigue charts of Fig. 6 that plot the $\sigma_{eff,max}$ to σ_{UTS} ratio vs. N_f confirm that the use of the TCD applied in the form of the Point Method and Line Method returned estimates mainly falling within the plain material scatter band. This result is certainly satisfactory since, from a statistical point of view, a predictive method cannot be more accurate than the experimental information used for its calibration.

CONCLUSIONS

According to the experimental/theoretical work that we have done in recent years at the University of Sheffield, UK, it is possible to come the conclusions summarised in what follows, where these conclusions are strictly valid solely for objects of PLA that are 3D-printed flat on the build plate.

- As the printing direction varies, E, $\sigma_{0.2\%}$ and σ_{UTS} are seen to be within two standard deviations of the mean.
- The mechanical behaviour of AM PLA can be modelled by treating this 3D-printed polymer as a linear-elastic material that is homogenous and isotropic.
- The effect of the printing direction on the overall fatigue strength of plain/notched AM PLA can be neglected with little loss of accuracy.
- The mean stress effect can be taken into account effectively by addressing the design problem in terms of maximum stress in the cycle, with this bolding true both in the presence and in the absence of notches.
- If appropriate experiments cannot be run, the fatigue strength of AM PLA can be assessed using a unifying design curve with k=5.5 and $\sigma_{MAX,Design}=0.1\sigma_{UTS}$ (at $2\cdot10^6$ cycles to failure for P_S=90%).
- The TCD is seen to be highly accurate also in assessing notch fatigue strength of AM PLA.

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FIGURE 1 Manufacturing direction and orientation of the deposition filaments.

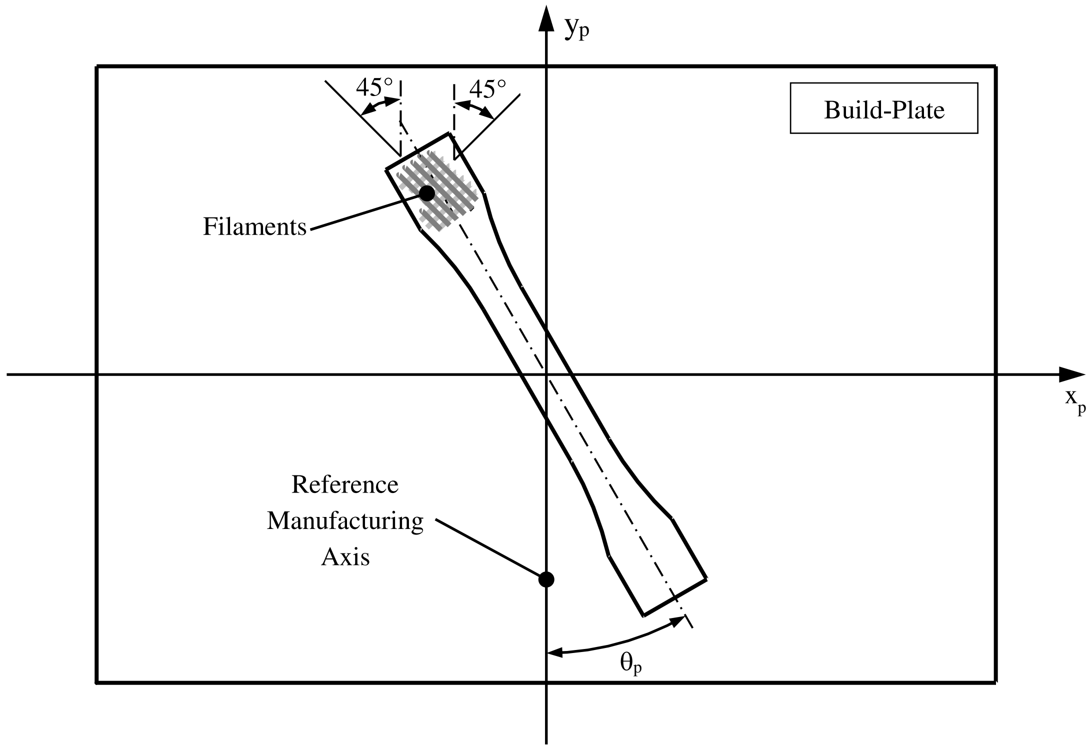

FIGURE 2 Experimental stress vs. strain curves generated by testing plain samples manufactured by adopting different values for manufacturing angle θ_p [1].

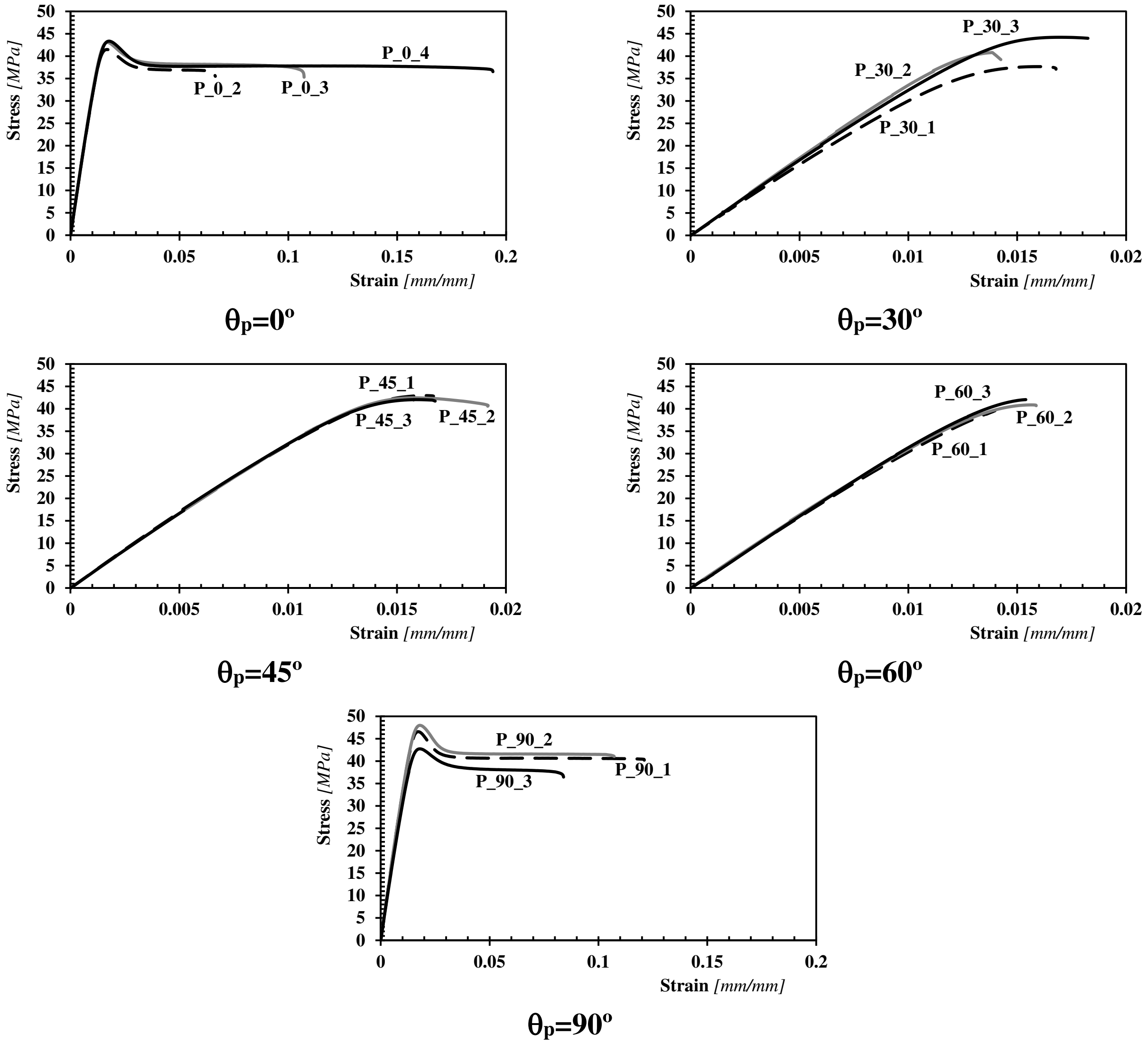

FIGURE 3 Influence of manufacturing angle θ_p on σ_{UTS}, $\sigma_{0.2\%}$ and E [1].

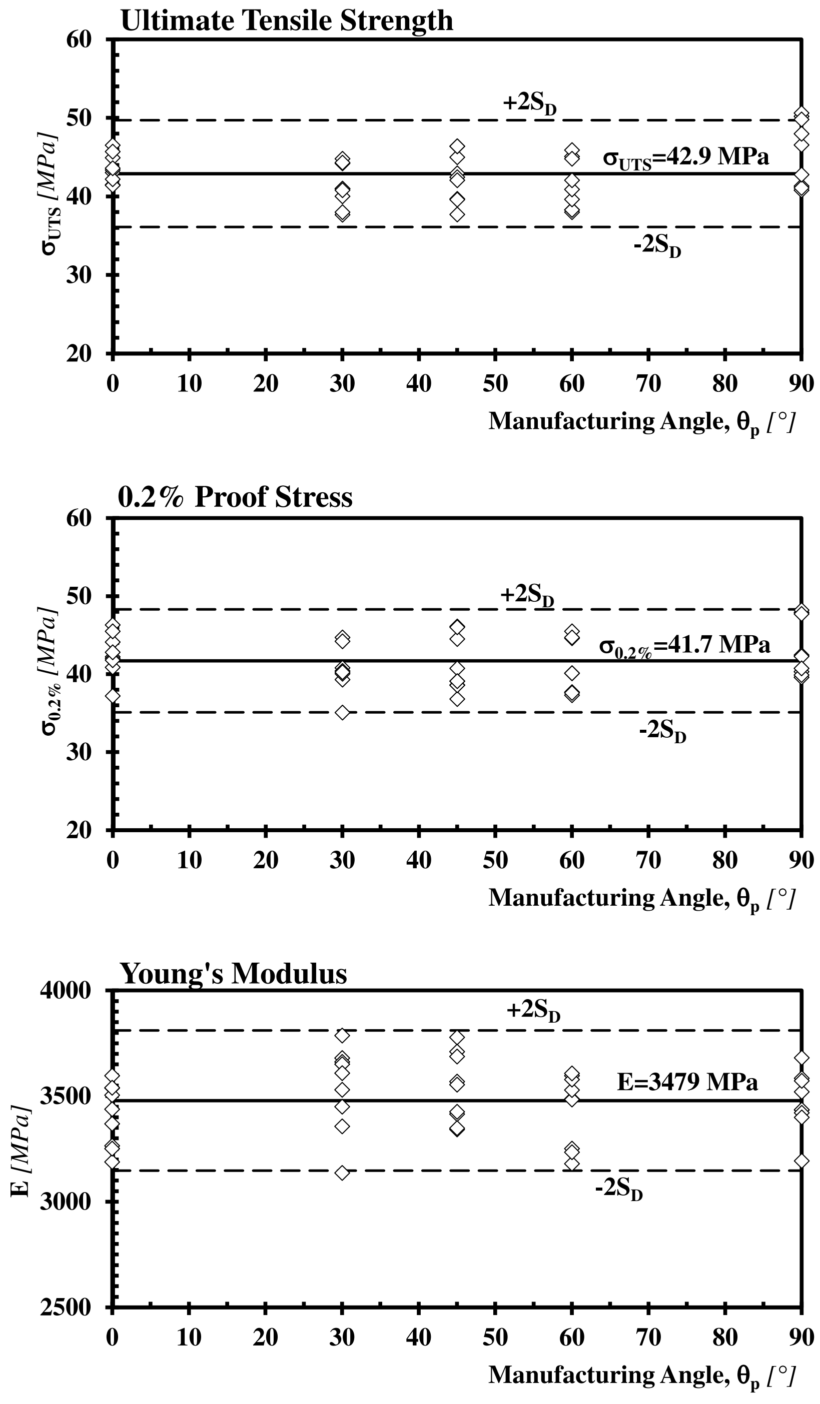

FIGURE 4 Unifying SN curve recommended to design AM PLA against fatigue [4].

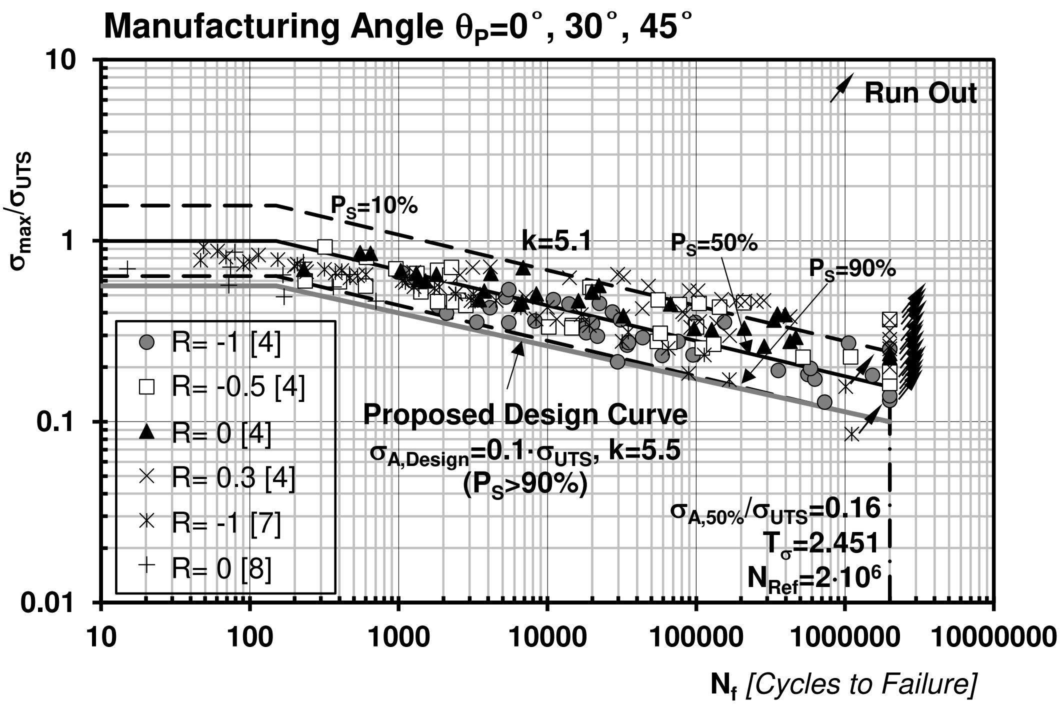

FIGURE 5 Notched component subjected to fatigue loading (a); the TCD applied in the form of the Point (b), Line (c) and Area Method (d); calibration of the LM vs. Nf relationship by using two different fatigue curves (e).

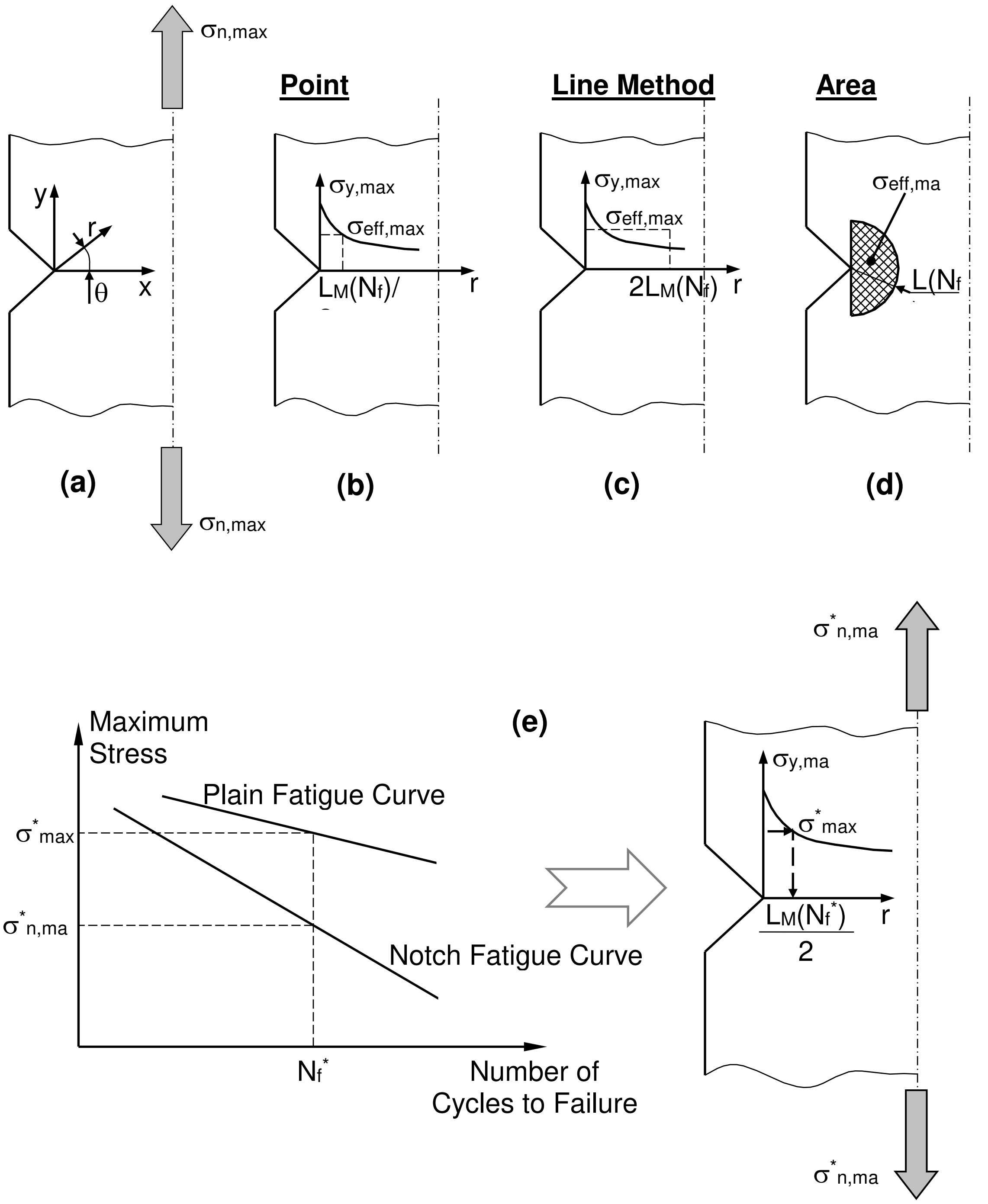

FIGURE 6 Accuracy of the TCD applied in the form of the Point and Area Method in estimating the fatigue lifetime of the notched specimens of AM PLA tested under axial fatigue loading.