Available online at www.sciencedirect.com

ScienceDirect

Structural Integrity Procedia 00 (2018) 000–000

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

AIAS 2018 International Conference on Stress Analysis

Fatigue strength of plastics components made in additive manufacturing: first experimental results

Mattia Frascio[a] *, Massimiliano Avalle[a], Margherita Monti[a]

[a] *Università degli Studi di Genova, Via all'Opera Pia 15, 16145 Genova, Italy*

Abstract

Evolution of additive manufacturing (AM) techniques is making these innovative technologies more and more available and known to a larger audience. This allowed components built with AM techniques, especially metallic ones, to be effective in substituting similar components made with traditional technologies; with all the advantages of AM that make these components even more interesting in terms of performance. With plastics this process is relented also due to the chronic lack of established knowledge of the plastic materials, both in terms of strength, design criteria, both in long term behavior but also in static short-term properties.
This work tries to give some useful information about the fatigue behavior of one class of material widely used with the mostly widespread AM technique for plastics, that is filament deposition modeling (FDM). The material considered is acrylonitrile-butadiene-styrene (ABS), used in countless components (electronic devices, household appliances, medical tools, and others) due to its excellent mechanical performances and relatively good workability.
The property mainly analyzed in this work is fatigue behavior. Fatigue tests were performed in plane bending on specimen very similar to the type proposed and used by Nicoletto (2018) in different manufacturing and loading conditions.
The obtained results offer an interesting insight into the properties of small components in ABS made by FDM and the effects of some influencing parameters: different stress-ratios were considered, as well as technological variations such as deposition direction. Experiments reveal that the scatter of fatigue data, even with the manufacturing uncertainties and defects typical of AM, can be controlled and within reasonable limits.

* Corresponding author. Tel.: +39-010-3532241; fax: +39-010-3532834.
E-mail address: mattia.frascio@edu.unige.it

Keywords: Fatigue of plastics; additive manufacturing.

1. Introduction

Additive Manufacturing (AM) is growing ever more interesting in engineering due to its advantages in freedom of design. At the same time costs have dropped especially for low-weight low-cost materials such as plastics. So, there is an increasing interest in proposing innovative solutions in many engineering applications. However, for technical applications it is of paramount importance to be able to design the new components and to predict their performance in any possible conditions, taking into account various environmental and loading conditions, to avoid any possible premature failure. This process, almost obvious for components made of conventional materials with conventional technologies, is still not completely established in components made of innovative materials (like for example plastics) and, for different but equally obvious reasons, even less with innovative technologies like additive manufacturing. The reasons for this lack of effective design methodologies lies not only in subjective insufficient know-how of the designers in this field and, sometimes, underestimated possible criticalities if not wrong assumption on some design approach, but also in the objective deficiencies of information and data in this area.

AM is a relatively young family of production technologies having the greatest flexibility and allowing the highest complexity due to the freedom from many technical constraints of conventional methods, and also enables optimization tools to be used at full potential, a remarkable e.g. by Primo et al. (2017). Actually, this *freedom* and *complexity at no costs* are not absolute and physical limitations together with new technological constraints still stand. First of all, strength of materials still dictates dimensional constraints together with other shape requirements. The problem in evaluating the strength of additively manufactured components lies in the intrinsic inhomogeneity and discontinuity of the material, whatever the used technology: whether starting from powders or filament, the layer-by-layer construction leaves a structure with countless microscopic defects. Orthotropic mechanical properties of Filament Deposition Modeling (FDM) parts have been investigated by several works experimentally, e.g. studying the effects of bed orientation, Cantrell et al. (2017), infill percentage and infill typology, Fernandez-Vincente et al. (2016), layer thickness and extrusion width, Corbett et al. (2014), extruder temperature, print speed, and layer height, Abbott et al. (2018). There are also interesting numerical, Sheth and Taylor (2017), and analytical, Casavola et al. (2016), approaches that correlate the orthotropic mechanical properties to the raster settings. The problem of evaluating the strength of such components is then obvious and even worse while dealing with fatigue.

Despite the relatively small age of AM there is a number of studies dedicated to fatigue. The fatigue of additively manufactured metal parts and components has been extensively analyzed and, among the others, the works from Nicoletto (2017)-(2018) offer an extensive set of very interesting and useful results showing the effects of manufacturing details.

Fatigue behavior of plastics has been studied almost since the beginning of the polymer age: many references and data already from the ’60 and ’70 of the twentieth century can be found in Moet and Aglan (1988). Specimen made with FDM were also manufactured to be examined in fatigue by Gomez-Gras et al. (2018), Letcher and Waytashek (2014), and Senatov et al. (2016) with PLA; Moore and Williams (2015) with elastomeric polymers; Fischer and Schöppner (2016) with PEI. ABS specimen built by FDM have also been examined by several authors: Carutasu et al. (2015) examined the basic tension/compression characteristics of ABS sample made by FDM; Dawoud et al. (2016) compared FDM with traditional molding techniques; Torrado et al. (2015) and Ziemian et al. (2012) examined the anisotropic behavior due to manufacturing and additives; Hart and Wetzel (2017) studied the fracture behavior; Gribbins and Steinhauer (2014) examined even a component, a living-hinge manufactured by FDM. Fatigue behavior of the ABS when manufactured in FDM also has been already examined: Ziemian et al. (2016) examined stiffness degradation caused by fatigue damage considering different mesostructures at various deposition angle, in cyclic tensile tests with a stress-ratio $R = 0.1$; Padzi et al. (2017) with similar loading conditions compared different forming methods, that is traditional molding and FDM; Lee and Huang (2013) also examined the deposition angle and direction; Zhang et al. (2017) instead considered alternate loading.

In the present work, loading in plane bending was considered: this loading mode demonstrated to be very convenient for AM components, as shown in several works by Nicoletto (2017)-(2018). Also, the effect of different stress-ratio R was considered. An extensive test campaign, considering the effect of deposition was performed. The analysis of the effects of these different parameters give a deep insight into the evaluation of the fatigue behavior of additively manufactured components made of ABS, and it will be a good basis for the design of components made of this material in FDM.

2. Approach and experimental details

2.1. Materials and FDM process

The FDM process was used to make the test samples of ABS filament by SIENOC with diameter of 1.75 mm. The test samples were fabricated using a Prusa i3 MK2S. The machine is equipped with a 0.4 mm nozzle single extruder, heated bed, open chamber with build volume of 10.5 dm^3. The FDM process took place positioning the specimens near the zero, long dimension parallel to *x*-axis, with a nozzle temperature of 250 °C and bed plate temperature of 100 °C. After fabrication the specimens were cooled down to room temperature on the bed plate in order to minimize swelling. In FDM there are many building parameters. A standard construction, with the aim of reducing manufacturing time but with sufficient strength and dimensional stability, corresponds typically up to 50% infill density and to parameters optimized by the machine manufacturer. In our case, to obtain a structure able of the highest mechanical strength, possibly comparable to the base material, were used modified parameters with a reduced 0.1 mm layer height, maximum nominal infill density (100%), and raster orientation ±45°, criss-cross along the layers relative to the longer dimension (Fig. 1).

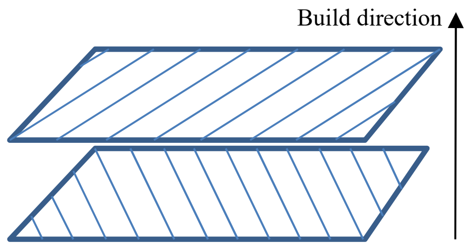


Fig. 1. Deposition pattern for the building of the FDM specimen.

For fatigue tests the specimen volume is 6189 mm^3, with a weight of 6.3 g, equivalent to a density of 1.017 kg/dm^3 that is 92.5% relative density.

Standard tensile samples built with the same parameter (volume is 1012.15 mm^3, weight 1.065 g, equivalent to a density of 1.052 kg/dm^3 or 95.6% relative density) were tested and provided the reference characteristics in Table 1. Fig. 2. shows the results of tensile tests on the material used: the behaviour is sufficiently repeatable in terms of strength and stiffness, with some scatter in terms of fracture elongation.

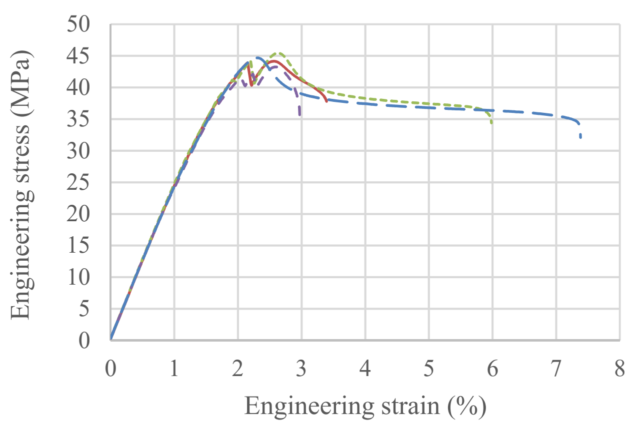


Fig. 2. Comparison of experimental tensile test results obtained using ISO 527, specimen 1BA.

Table 1. Statistics of tensile tests, data obtained using ISO 527, specimen 1BA.

Results	Tensile modulus E (MPa)	Yield strength σ_y (MPa)	Yield strain ε_y (%)	Elongation at break ε_b (%)
Average	2470	44.8	2.5	5.6
Standard deviation	19.4	0.652	0.23	2.0
Coefficient of variation %	0.79	1.46	9.27	36.2

As a reference, Table 2 reports some nominal and experimental data about the strength of the base material for the SIENOC filament compared with the ABS from other producers.

Table 2. Experimental tensile properties and comparison of ABS filaments, ABS specimens and ABS in FDM.

Property	Filament as is, SIENOC	Heated, not extruded, SIENOC	ABS Stratasis	ABSi Stratasis	ABSplus Stratasis	ABS Ultimaker	Ultimaker, injection molding
Break stress (MPa)	34.4	45.3	22	37	36	33.9	43.6
Tensile modulus (MPa)	1080	1740	1627	1915	2265	1681.5	2030
Elongation at break (%)	4.2	3.1	6	3.1	4	4.8	34

2.2. Fatigue specimen geometry

In this study the specimen geometry specially developed by Nicoletto for additive manufacturing was used after scaling by 2:1 to be adapted for polymeric materials (Fig. 3). The original specimen would have been too small and the forces too little for a proper measurement.

This specimen is designed to be tested with plane cyclic bending loading. It is essentially prismatic, 46 mm in length, 10×10 mm^2 minimum cross section, 10×14 mm^2 gross section with a lateral semi-circular notch 4 mm radius (Fig. 3).

The advantages of this miniaturized geometry are the reduction of material, the absence of supports need, required and mostly the remarkable reduction of production time, a sensitive issue for fatigue qualification.

Three build direction were investigated in order to study the directionality fatigue behaviour under the same nominal bending stress. Fig. 4 shows the positioning on the build plate and respective denomination.

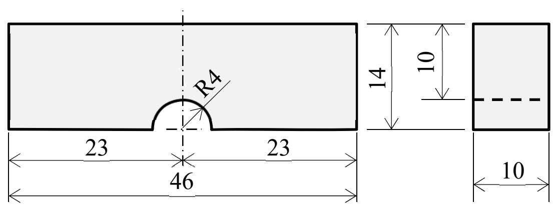


Fig. 3. Specimen geometry.

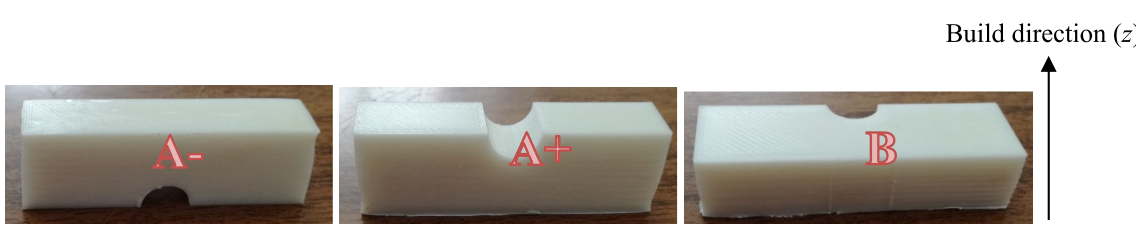


Fig. 4. Specimens used in the experimental program, oriented according to the build direction.

2.3. Fatigue testing program

Fatigue experiments were performed using a Schenk PK103 fatigue testing machine modified to apply plane bending load to flat specimen. A load cell was added to the system to continuously monitoring the true load applied to the specimen during cycling. Due to the characteristics of the machine, the bending load was applied in displacement control, at 25 Hz frequency. Consequently, the load being monitored was applied with stress amplitude in a range between 4 MPa and 33 MPa. As it is well known, in displacement control the fracture does not occur explicitly: as soon as the fatigue crack nucleate and propagate the specimen compliance will increase. Crack propagation can even no longer continue and, to detect fatigue failure, compliance measurement must be done. For this reason, the load was continuously monitored, and failure was considered as soon as the stiffness decreased of 10% with respect to the initial value.

Six sets of specimens were tested, two for each build direction (Fig. 4), one under bending moment with $R = 0$ and one under bending moment with $R = -1$ (see Table 3): in Fig. 5 two examples of the signal acquired during 1 s is shown. The stress indicated is the nominal stress computed with the simpler linear stress distribution of the bending of beams: the curves reported in Fig. 5 meant to verify the correct load application to the samples.

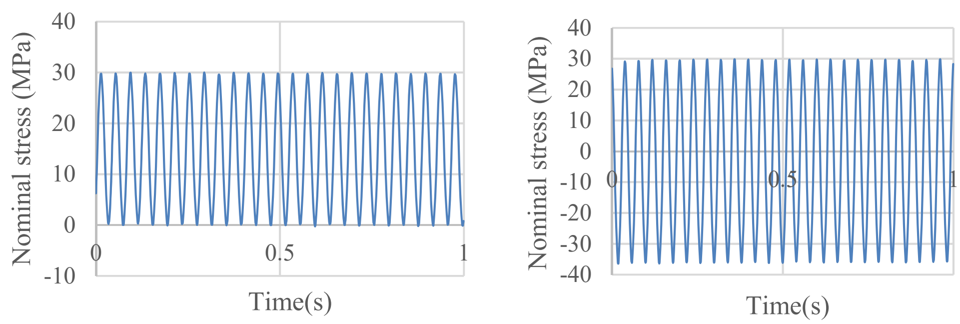


Fig. 5. Two examples of the load signal acquired during tests: (a) σ_a = 15 MPa, $R = 0$; (b) σ_a = 30 MPa, $R = -1$.

Table 3. Experimental plan.

Configuration	Load type	Nominal stress amplitude range (MPa)
 A-	$R = 0$ $R = -1$	4 - 16.5 8 - 33
 A+	$R = 0$ $R = -1$	4 - 16.5 8 - 33
 B	$R = 0$ $R = -1$	4 - 16.5 8 - 33

As also shown by Nicoletto (2016) the specimen geometry introduces a non-linearity in the distribution of the stresses through the thickness. The notch creates a stress increase evaluated in 1.56 in the cited work. For comparison the stress-ratio between the actual maximum stress and the nominal maximum stress calculated for a rectangular section under bending moment can be estimated equal to 1.597 with ANSYS 17.2 and only 1.497 with Altair OptiStruct 2017 (Fig. 6). The average value of 1.55 very near the value proposed by Nicoletto (2016) will be adopted. The current model also considers a linear elastic material model since, from the experimental results shown in §2.1, for the level of maximum stress reached during fatigue testing the material still behaves as perfectly elastic.

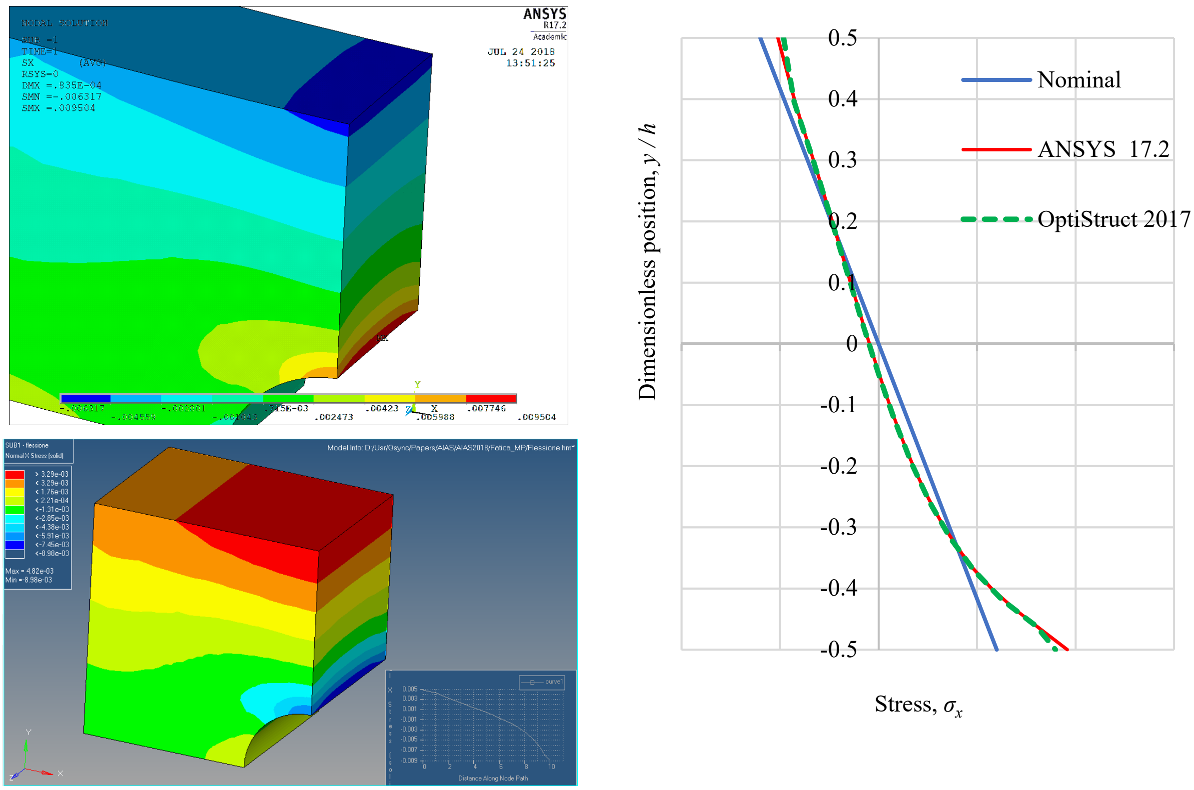


Fig. 6. Stress distribution through the section calculated by two FE codes: ANSYS 17.2 (top) and Altair OptiStruct 2017 (below). On the right the comparison along the transverse mid-section.

3. Results and discussion

3.1. Reference fatigue behavior of FDM ABS

The fatigue of ABS has been examined in several works already mentioned in the introduction. Fig. 7 compares some recent results in terms of S-N curves for apparently equivalent ABS samples, loaded in similar conditions, that is all loaded with a stress-ratio $R = 0.1$. At a first glance it appears that large variations, expected with polymers, are observed: in some cases, a factor around two is found between the largest and smallest value of strength at the same endurance. The slope of the S-N curve is similar in most cases but there are different trends in some published data.

A further similar comparison is given in Fig. 8 where results of tests on ABS samples made with AM technologies are compared (data from Zhang (2017) are not reported since they excessively deviate, of around one order of magnitude, from all the other literature results). In this case also, significant differences are found: unexpectedly the largest values, for equal endurance, are not much less than the smallest obtained from traditional injection molding results in Fig. 7.

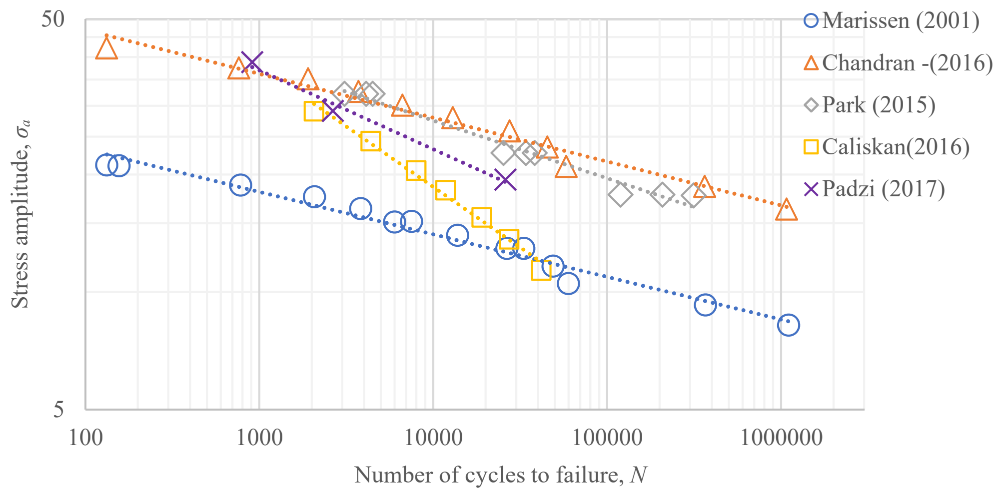


Fig. 7. Comparison of the S-N curves for ABS from various literature sources.

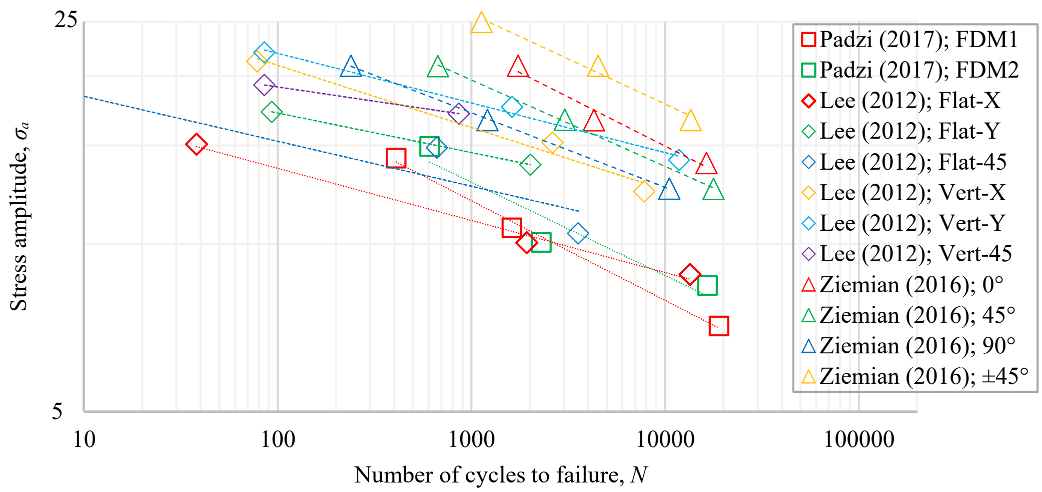


Fig. 8. Comparison of the S-N curves for ABS samples made with FDM from various literature sources.

3.2. Directional fatigue behavior

Results from fatigue testing on the samples gave interesting information: the scatter was relatively contained despite the various sources of uncertainties due to the unavoidable manufacturing defects including poor surface finish (each sample was tested *as is* that is without surface modifications) and the typical internal defects of FDM. However, the S-N curves showed well defined and reasonable trends that will be discussed.

Fig. 9 reports a comparison between the S-N curves obtained from the A samples in the two deposing orientations. From a first observation there is a clear influence of the stress-ratio. Curiously, the influence is not the same and A-samples were much more affected by the different stress-ratio, especially in the low range of endurance, mostly because the build direction with the notch faced down is critical for geometry accuracy.

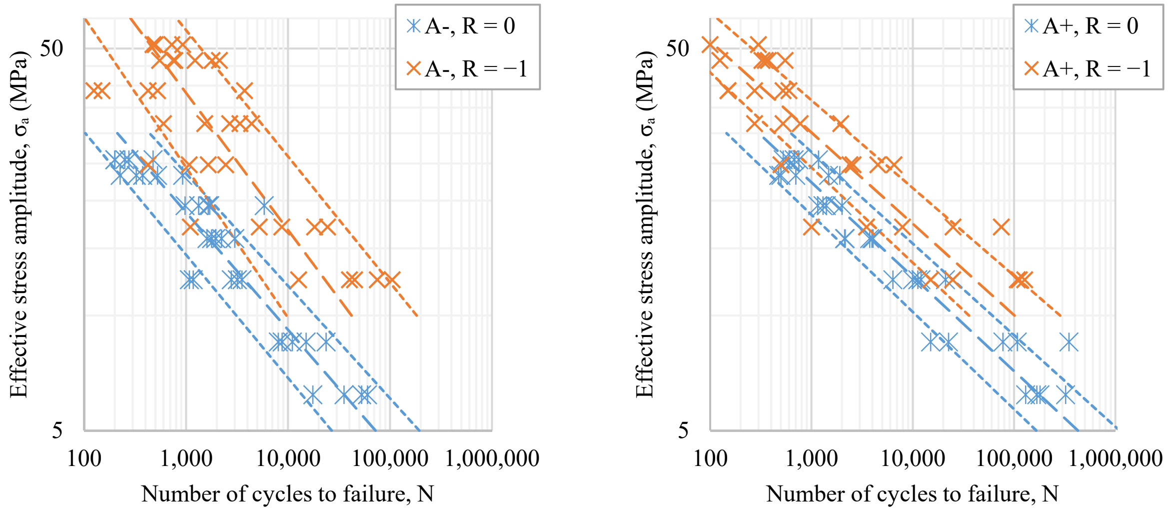


Fig. 9. Comparison of the experimental S-N curves for the A orientation samples: effect of the stress-ratio.

The second comparison is, for the same stress-ratio, between the two deposition directions for specimen A (Fig. 10). In this case, the difference appears less significant especially for stress-ratio equal to −1: the two samples seem from a same population meaning that the direction has a limited impact for some values of the endurance.

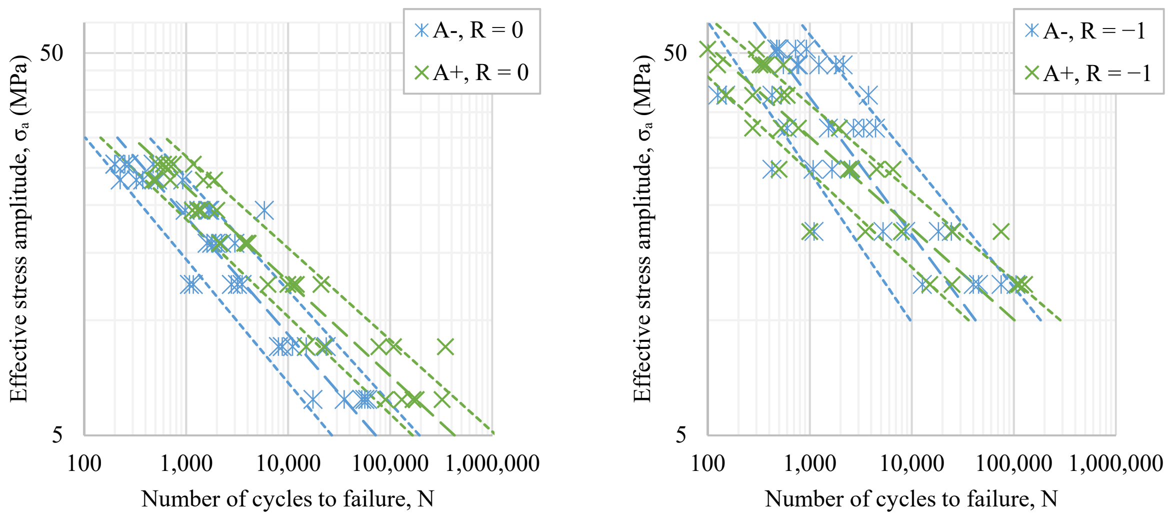


Fig. 10. Comparison of the experimental S-N curves for the A orientation samples: effect of the deposition direction.

Last, the same comparison as in Fig. 9 is reported for the B samples (Fig. 11). Similar conclusions can be drawn and a clear effect of the stress-ratio occurs, almost independent of the number of cycles to failure.

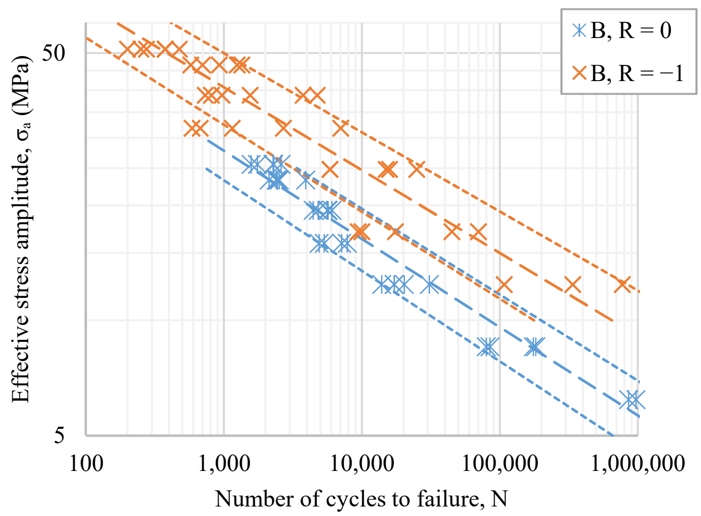
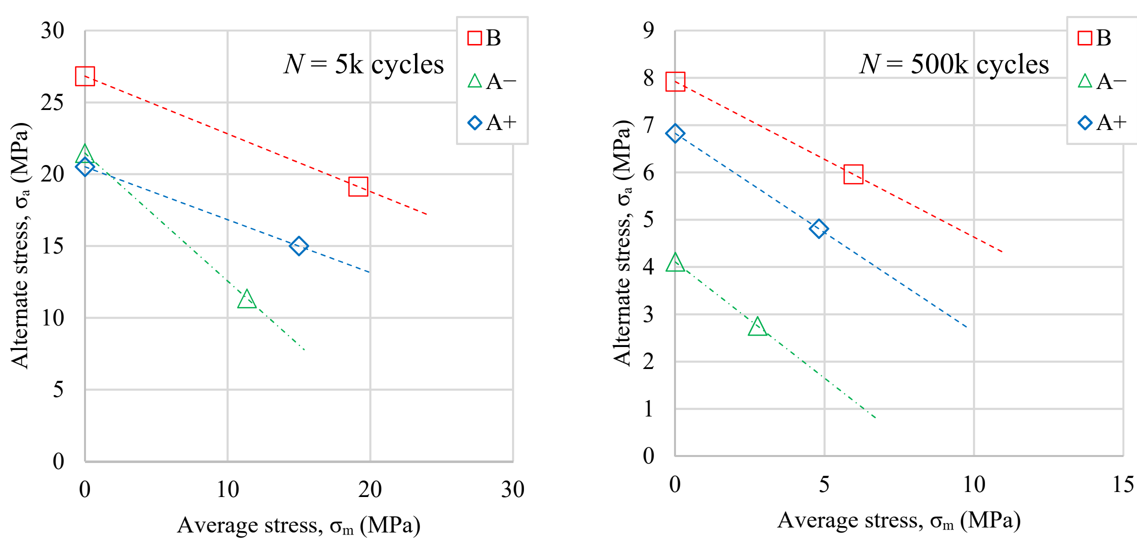


Fig. 11. Comparison of the experimental S-N curves for the B orientation samples: effect of the deposition direction.

Apparently, deposition, as in the case of the B samples, gives slightly superior fatigue strength. For example, if reporting the estimated average fatigue strength corresponding to values of the endurance of 5×10^3 and 5×10^5 cycles (Fig. 12), its value is around 20-25% higher. It is interesting also to note that, as also observed from Fig. 10 that the effect of the deposition direction is different depending on the endurance: strength is nearly the same at lower number of cycles and diverges at higher duration. This aspect, worth of further investigation, is apparently not of statistical nature since a large number of samples was evaluated at the stress level of interest. Some discussion is also added in the next paragraph.



(a) (b)

Fig. 12. Effect of the stress-ratio on the fatigue strength of the examined ABS produced by AM: estimated average values for two level of endurance: (a) 5×10^3 cycles to failure; (b) 5×10^5 cycles to failure.

3.3. Discussion and comparison with the literature

This work enriches the published FDM data of tensile properties and axial fatigue that can be found in the literature describing the fatigue behaviour of as built ABS under an applied cyclic bending load. Parameters were maintained as standard as possible in order to obtain less machine specific results and increase the comparability, anyway difficult due to the many blends of ABS available on the market.

Observing data in section §3.2, and the literature ones, a certain scatter can be noticed. This is worth to be more investigated because, from the studies on components build with traditional process, it is well known that fatigue failure at high stress level are due to defects, but at low stress level failures should be mostly function of the specific material. It is also known that a certain level of internal defects is intrinsic to the FDM process that use a continuous filament (void and approximation at curvatures) and as trade-off between geometry precision and adhesion, as shown by Gibson et al. (2015), see Fig. 13.

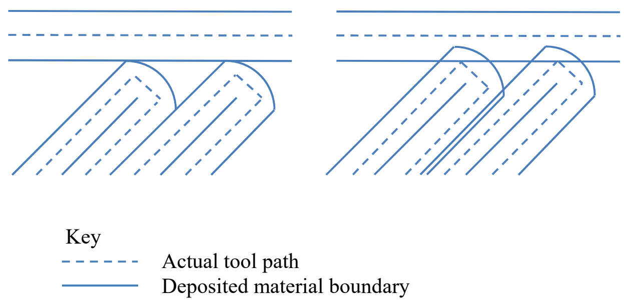


Fig. 13. Examples of different possible tool path and the effects on the geometry, adhesion and voids.

The specimens to be investigated were selected at lower and upper range of cycle life at failure for each stress level.

Observing the magnified surfaces of the specimens, it was possible to point out some remarks. The ones at lower end present typically two characteristic situations (Fig. 14):

- Incorrect control of the deposition temperature of the filament: a temperature lower than the optimal prevents the correct adhesion between layers and the sides of the filament along the pattern in the raster. Not easy to be noticed by eye, it is a critical problem because its effect is a decrease of the actual section of the component. In Fig. 14(a) critical configuration is shown: the resistance is given almost only by the filament at some joined points. The signs of crack propagation on the fracture surface remarks the inhomogeneous mechanical properties of the material. On the other hand, setting higher temperatures causes local degradation of the polymeric materials.
- Inaccuracy in the position of the filament: it is attributable to the open loop control or imperfect hardware configuration. In this case the filaments and the layers are well bonded, but the deposition errors create critical points that start the crack propagation (Fig. 15). This problem is solvable by improving the machine calibration.

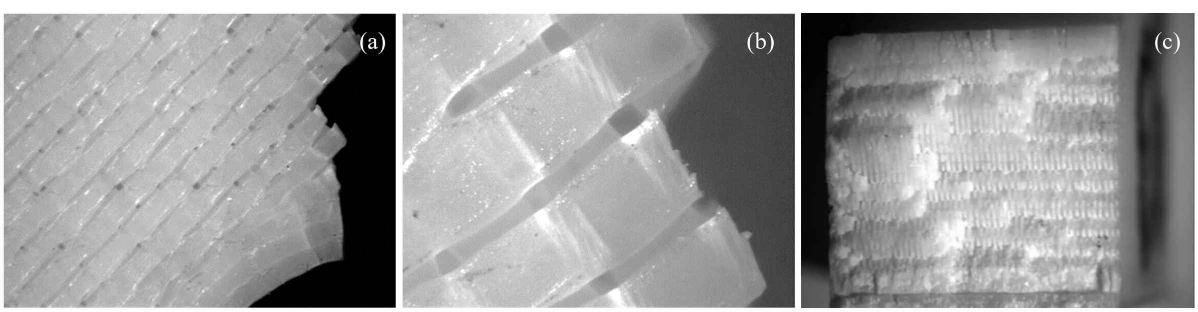


Fig. 14. Observed defects: (a) inaccuracy on temperature of deposition; 12×; (b) detail of the fracture, 50×; (c) fracture surface, 6×.

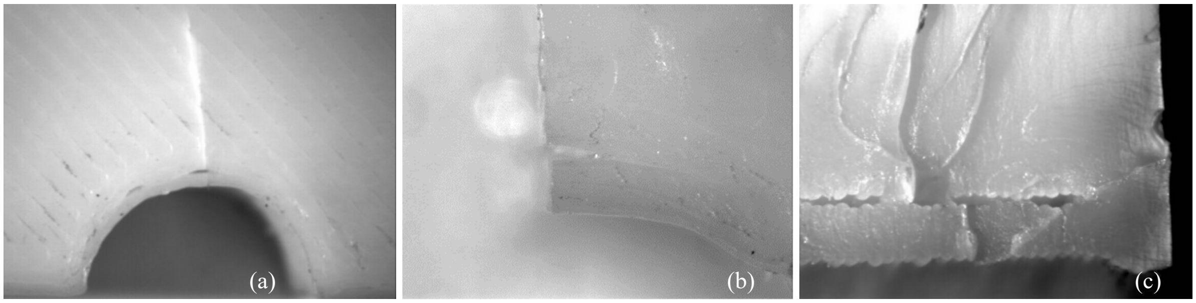


Fig. 15. Observed problems: (a) inaccuracy on filament positioning, 6×; (b) Detail of the fracture surface, 25×, (c) fracture surface, 25×.

While investigating the samples with the longest endurance at each tested stress level, it is apparent that they have both external surface and cross section smooth and well packed: this is a confirmation of a more accurate deposition temperature and filament positioning. By comparing Fig. 14 and Fig. 16, it is remarkable that on the fracture surface is almost impossible to distinguish the cross section of the filament.

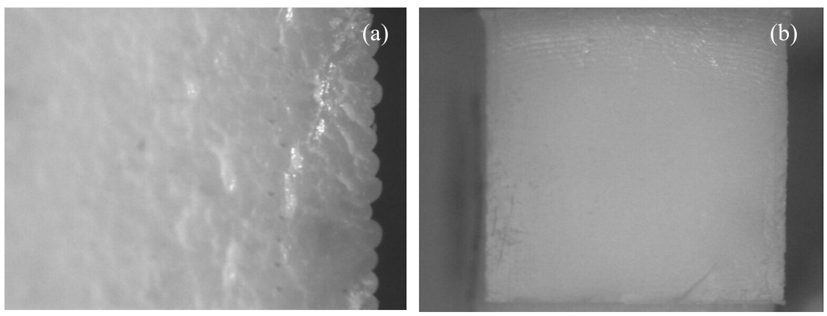


Fig. 16. Detail of the fracture surface of samples, in the upper range of life cycle: (a) 50× magnification; (b) 6×.

Finally, comparing our experimental results with data found in the literature it can be noticed that they stay within the average if not at the upper limits: a direct comparison is hard to perform seen the uncertainties in the actual type of material, technology and manufacturing parameters, and the different type of specimen. However, the presented data are compatible with others and add some additional insight into some important influencing factor as the presence of a constant stress added to the alternate component.

4. Conclusions

The paper presented some experimental results about the fatigue strength of additively manufactured samples of ABS. The experiments were performed in plane stress conditions with two different values of the stress-ratio. S-N curves were obtained loading at different levels of stress amplitude to obtain values of the endurance from around 10^3 to 10^6 cycles to failure. An innovative type of specimen, equivalent to the type used by Nicoletto in his papers, was used: this type of specimen is nearly prismatic with a central notch. The main difference was the size, doubled along all directions, to be more suitable to the lower strength of the plastic material used.

The obtained results confirm the known effect of the stress-ratio and show limited scattering despite the, almost unavoidable, presence of defects in the AM parts. On the contrary, less important effect has been observed due to the manufacturing details, especially the different deposition directions.

The obtained results, even with the limitations of the limited number of tests and stress-ratios examined, give some interesting insights on the fatigue strength of components realized in additive manufacturing and add knowledge in this still not completely explored field.

References

Abbott, A., Tandon, G., Bradford, R., Koerner, H., Baur, J., 2018. Process-structure-property effects on ABS Bond strength In fused filament fabrication. Additive Manufacturing 19, 29-38.

Cantrell, J., Rohde, S., Damiani, D., Gurnani., R, DiSandro, L., Anton, J., Young, A., Jerez, A., Steinbach, D., Kroese, C., Ifju, P., 2017. Experimental characterization of the mechanical properties of 3D-printed ABS and polycarbonate parts. In *"Advancement of Optical Methods in Experimental Mechanics, Volume 3"*. Yoshida, S., Lamberti, L., Sciammarella, L. (Eds.). Springer, Cham (CH), pp. 89-105.

Casavola, C., Gazzato, A., Moramarco, V., 2016. Orthotropic mechanical properties of fused deposition modelling parts described by classical laminate theory, Materials and Design 90, 453–458.

Carutasu, N.L., Simion, J., Carutasu, G., Jiga, G., Arion, A.F., 2015. Experimental Test for Elastic and Mechanical Evaluation of ABS Plastic Used in 3D Printing. Materiale Plastice 52, 397-401.

Corbett, T., Kok, T., Lee, C., Smith, S., Villaraga, H., Tarbutton, J., 2014. Identification of mechanical and fatigue characteristics of polymers fabricated by additive manufacturing process. ASPE Spring Topical Meeting 57, 186-189.

Dawoud, M., Taha, I, Ebeid, S.J., 2016. Mechanical behaviour of ABS: An experimental study using FDM and injection moulding techniques. Journal of Manufacturing Processes 21, 39-45.

Fernandez-Vicente, M., Calle, W., Ferrandiz, S, Conejero, A, 2016. Effect of Infill Parameters on Tensile Mechanical Behavior in Desktop 3D Printing. 3D Printing And Additive Manufacturing 3(3), 183-192.

Fischer, M., Schöppner, V., 2016. Fatigue behavior of FDM parts manufactured with ULTEM 9085. The Journal of The Minerals, Metals & Materials Society 69, 563-568.

Gibson, I., Rosen, D., Stucker, B., 2015. Additive manufacturing Technologies, Springer-Verlag New York.

Gomez-Gras, G., Jerez-Mesa, R., Travieso-Rodriguez, J.A., Lluma-Fuentes, J., 2018. Fatigue performance of fused filament fabrication PLA specimens. Materials and Design 140, 278-285.

Gribbins, C., Steinhauer, H.M., 2014. Experimental analysis on an additively manufactured ABS living hinge. 25th Annual International Solid Freeform Fabrication Symposium, Austin (TX), USA, paper #111.

Hart, K.R., Wetzel, E.D., 2017. Fracture behavior of additively manufactured acrylonitrile butadiene styrene (ABS) materials. Engineering Fracture Mechanics 177, 1-13.

Lee, J., Huang, A., 2013. Fatigue analysis of FDM materials. Rapid Prototyping Journal, 19(4), 291-299.

Letcher, T., Waytashek, M., 2014. Material property testing of 3D-printed specimen in PLA on an entry-level 3D printer. In ASME 2014 International Mechanical Engineering Congress and Exposition. American Society of Mechanical Engineers.

Moet, A., Aglan, H., 1988. Faigue Failure. In: Engineered Materials Handbook Volume 2: Engineering Plastics. ASM International, Metals Park, OH, pp. 741-750.

Moore, J.P., Williams, C.B., 2015. Fatigue properties of parts printed by PolyJet material jetting. Rapid Prototyping Journal 21., 675-685.

Nicoletto, G., 2018. Directional and notch effects on the fatigue behavior of as-built DMLS Ti6Al4V. International Journal of Fatigue 16, 124-131.

Nicoletto, G., 2017. A novel test method for the fatigue characterization of metal powder bed fused alloys. Procedia Structural Integrity 7, 67-74.

Nicoletto, G., 2018. Efficient determination of influence factors in fatigue of additive manufactured metals. Procedia Structural Integrity 8, 184-191.

Padzi, M.M., Bazin, M.M., Muhamad, W.M.W., 2017. Fatigue Characteristics of 3D Printed Acrylonitrile Butadiene Styrene (ABS). IOP Conferences Series: Materials Science and Engineering 269, paper 012060.

Primo, T., Calabrese, M., Del Prete, A., Anglani, A., 2017. Additive manufacturing integration with topology optimization methodology for innovative product design. International Journal of Manufacturing Technologies 93, 467-479.

Senatov, F.S., Niaza, K.V., Stepashkin, A.A., Kaloshkin, S.D., 2016. Low-cycle fatigue behavior of 3d-printed PLA-based porous scaffolds. Composites Part B 97, 193-200.

Sheth, S., Taylor, R., 2017. Numerical Investigation of Stiffness Properties of FDM Parts as a Function of Raster Orientation. Solid Freeform Fabrication, Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, pp. 1112-1120.

Torrado, A.R., Shemelya, C.M. English, J.D, Lin, Y., Wicker, R.B., Roberson, D.A., 2015. Characterizing the effect of additives to ABS on the mechanical property anisotropy of specimens fabricated by material extrusion 3D printing. Additive Manufacturing 6, 16-29.

Zhang, H., Cai, L., Golub, M., Zhang, Y., Yang, X., Schlarman, K., Zhang, J. 2017. Tensile, Creep, and Fatigue Behaviors of 3D-Printed Acrylonitrile Butadiene Styrene. Journal of Materials Engineering and Performance 27, 57-62.

Ziemian, C., Sharma, M., Ziemian, S., 2012. Anisotropic Mechanical Properties of ABS Parts Fabricated by Fused Deposition Modelling. In: Gokcek, M. (Ed.). Intech, Rijeka (HR), 159-180.

Ziemian, C.W., Ziemian, R.D., Haile, K.V., 2016. Characterization of stiffness degradation caused by fatigue damage of additive manufactured parts. Materials and Design 109, 209-218.