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USING OWN ALGORITHMS TO INCREASE THE QUALITY AND FATIGUE RESISTANCE OF FDM PRINTING FOR USE IN DRONES AND SMALL AIRCRAFT

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Abstract

The present article discusses the three-dimensional (3D) printing process in the fused deposition modeling (FDM) or the fused filament fabrication (FFF) technique using the author's own philosophy of shaping the printing head path. The main requirements are the possibility of eliminating supports and reducing or even eliminating the need for the mechanical processing of 3D prints before their final assembly. The presented methodology was implemented in a computer program written by the author and was used to print typical parts used in aviation. Individual methods of shaping parts typical for the construction of small flying models, such as wings and fuselages, and methods of strengthening and connecting them have been discussed. The proposed solutions are illustrated with photos of readymade prints. This article also discusses the issues that printing high-quality parts may encounter and how to avoid them. Some attention has also been paid to the materials used for printing and their suitability in the construction of aircraft and their fatigue strength.

Keywords: FDM, FFF, 3D printing, PLA, ABS, polymer, fatigue
Article category: research article

Introduction

The three-dimensional (3D) printing technique using the fused deposition modeling (FDM) method has become a very popular method of producing polymer elements in the last decade (France, 2014). Its undoubted advantages are simplicity, low price, and availability. The possibility of producing elements with almost any geometry, often unavailable with other manufacturing techniques, is undoubtedly a novelty in the current technological state-of-the-art. The average user of this technology uses typical software available on the market, often free of charge, to create programs for a 3D printer. Thanks to the creators of this software, 3D printing could easily develop and be available to everyone. However, printing elements for specific purposes requires a more sophisticated approach than that proposed by the developers of general-purpose programs. The use of a dedicated philosophy of shaping parts and the resulting requirement of our own computer program mean that aircraft parts can be made cheaper and faster and they can be light and of high quality. This article describes methods of printing without the use of supports and also without the need to use semi-monocoque geodetic structures. The main emphasis was placed on shaping the monocoque and semi-monocoque structures as best suited for 3D printing. The proposed method of strengthening semi-monocoque structures is typical of the solutions used so far in the construction of aircraft structures and does not require oblique guidance of load-bearing elements.

General characteristics of the FDM printing process

3D printing using the FDM method, also known as fused filament fabrication (FFF), involves melting the filament in the printing head and then extruding an appropriate portion of the semiliquid filament in an appropriate place, where it is cooled and solidified again. In this printing method, layer by layer is applied, starting with the first layer placed on the print bed (that is often heated to improve adhesion). The printing scheme with this method is provided in Figure 1.

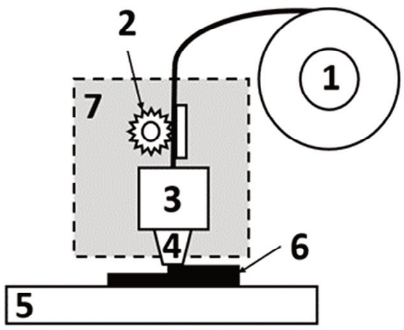

Figure 1. Scheme of 3D printing in the FDM method: 1 – filament spool, 2 – filament dispensing gear, 3 – heating block, 4 – nozzle (hot end), 5 – print bed, 6 – printed element, 7 – extruder (gray).

The filament is unwound from spool 1 using a gear 2 driven by a stepper motor. The filament then goes to the heating block 3, where it changes its state to semiliquid and then moves to the nozzle, where it is formed and placed in the appropriate place in the print 6. The print rests on the print bed 5, which is moved in both directions in the horizontal plane. Control in the vertical direction (transition to the next layer) is carried out by the vertical movement of the extruder module 7.

In the 3D printing process supported by the available software called slicer (that is used for cutting 3D models into layers and for determining the working path of the printing head), the working stroke during which the material is applied is interwoven with the non-working movement which is intended to move the printing head to a new position on the same printing plane. During the non-working movement, the extruder does not extrude the molten material, but this is only a theoretical assumption. Although the extruder gear does not receive any signal to move, in reality the material is already so liquid after passing the heating block, that it flows out under its own weight through the nozzle. During the non-working movement, the material is additionally pulled out of the nozzle by cohesive forces with the already-placed material, because it is not cut off or held back in the nozzle in any way. Spontaneous leakage of filament from the nozzle results in a shortage of molten material in the nozzle, which causes a shortage of material when the next printing track begins. As a result, the print in this place has holes, and the layers are not well fused together. Such a print is not only unsightly, but also very weakened and leaky. Therefore, when designing the correct tool path, this phenomenon should be taken into account. The diagram of the filament's transition from a solid to a semiliquid state and its re-solidification is shown in Figure 2. The range of the solid filament is marked in blue, while the red color indicates the filament in liquid form.

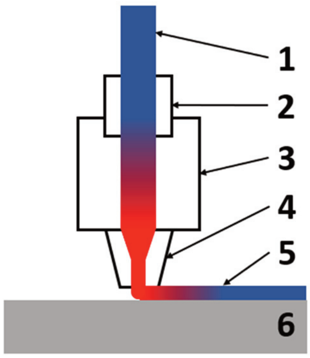

Figure 2. Scheme of the filament path through the extruder: 1 – filament, 2 – tube introducing the solid filament, 3 – heating block, 4 – nozzle (hot end), 5 – applied layer of molten filament, and 6 – print.

The proposed path of the printing head is determined assuming that the printing head does not run beyond the print contour. Owing to this aspect, the head is always in contact with the print, which naturally blocks the flow of material through the nozzle.

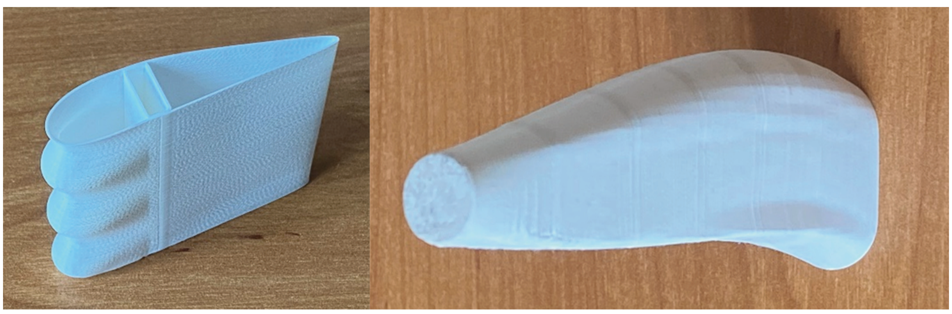

Figure 3. Elements with complex geometry, easily made using FDM printing. FDM, fused deposition modeling.

Typical elements found in the construction of flying models and drones are fuselages and wings (Fig. 3). These are slender elements with a cross-section, usually round, elliptical, or of a shape of an airfoil. They may be untapered, tapered, or have a transition from one shape to another (e.g., aerodynamic twist). The type of structure of the fuselage and wing may be wireframe, semi-monocoque, or monocoque. Due to the fact that the FDM 3D printing method is poor at producing monolithic spatial wireframes, semi-monocoque and monocoque structures are of greater interest (Fig. 4).

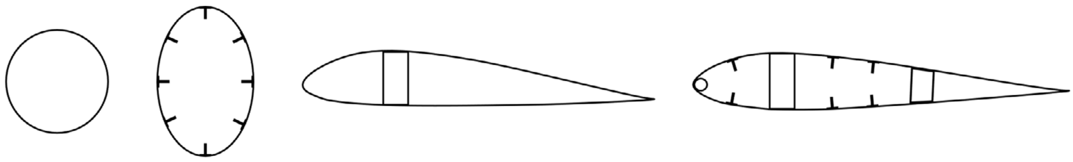

Figure 4. Cross-sections of typical elements used in the construction of flying models.

Printing of the monocoque structures is relatively simple, especially when the shell thickness is constant. Printing of the semi-monocoque structures involves printing the outer shell and its inner reinforcements, using the shell as the main part of the print along which the printing head moves (Fig. 5).

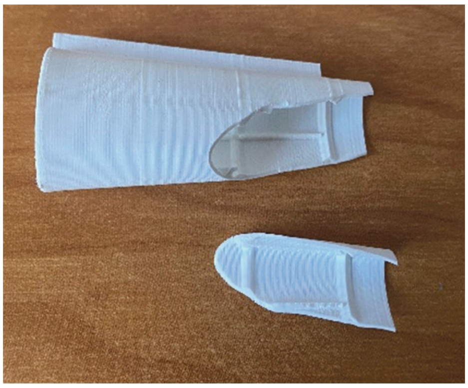

Figure 5. Section of a typical semi-monocoque structure of a fuselage.
FDM, fused deposition modeling.

Printing directions

The designation of the printing directions used in typical programs for cutting solids (so-called slicers) is shown in Figure 6. The X and Y directions create a printing plane parallel to the print table plane, while Z is the direction of the vertical guides, responsible for the transition to printing the next layer. The Z axis is a direction along which the extruder moves.

FDM printing takes place on a table on which molten filament is placed with the positioning accuracy of the lead screws. Manufacturers of typical desktop printers provide accuracy of 0.1 ÷ 0.05 mm for the X and Y directions. However, printing in the Z direction is stepped, where the height of the step is equal to the height of layer h, as shown in Figure 7.

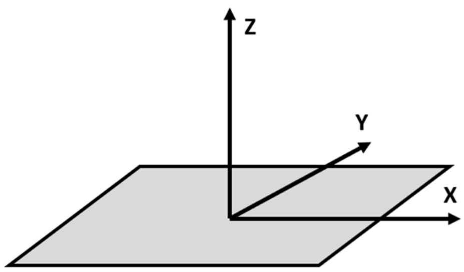

Figure 6. Printing directions in the FDM method. FDM, fused deposition modeling.

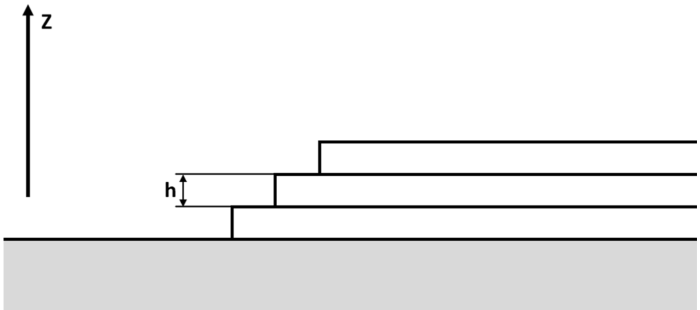

Figure 7. Print layering in the Z direction.

The layer thickness is not a fixed value, but must be a multiple of the smallest step that the lead screw can take in the Z direction. It is usually an element of the same construction as the guides in the X and Y directions, so the step is 0.1 mm or 0.05 mm in better-quality printers.

The strength of the print material is not the same in every place of the finished print, and the material is not isotropic after application. This is because the layers may be better or worse melted together, especially in large prints, where the melted material is placed on top of the completely solidified material. Hence, 3D FDM prints most often crack at the layer boundaries. For this reason, the Z-direction is not recommended for the longest dimension of elements transferring large bending moments; the Z direction should not be the longitudinal axis of any type of spars.

Load-bearing elements, such as wings and stabilizers, are characterized by high slenderness (with low shape variability along the span), but require high quality of surface fabrication for aerodynamic reasons. Because of that, the direction of printing along the span is the best one from the point of view of the quality of the outer surface. In case of wing, this is also the worst possible printing direction from the point of view of high bending strength. The situation is similar with fuselage elements, which are also subject to significant bending—especially in the classic aircraft layout. However, the fuselage may be characterized by much greater shape variability along its longitudinal axis than a typical wing. The printing orientation is the parameter that has the greatest impact on the stiffness of the part and the maximum deformation (Travieso-Rodriguez, 2019).

The solution to this problem may be to strengthen printed elements with stringers that transfer bending loads. These may be monolithic printed stringers or additional elements that require assembly and gluing (bu it this case the monolithic nature of the structure suffers). These additional elements may be printed using the FDM technique, but using the best printing orientation to ensure their durability, or they can be non-printed elements, that are produced using a different technology, e.g., carbon roving stringers. This makes possible to use elements with a strength several times higher than the print material, but also to use elements that have no restrictions on their length (so typical for 3D printing). In extreme cases, 3D printing can then be treated as a high-quality 3D fairing, the loads of which are almost exclusively carried by non-printed elements.

Thickness of the printed layer

As already mentioned, the layer height must be a multiple of the smallest guide movement in the Z direction; most often it is 0.05 mm. This printout is then considered accurate. A layer thickness of 0.1 mm defines the print as good, while a thickness of 0.2 mm defines it as quick—prototype. The layer height affects the dimensional accuracy of the print and the print time (this is probably the most frequently mentioned and known relationship). Thickness also has a large impact on the feasibility of certain print details when it comes to the printing of thin shells.

Figure 8 shows the print of a thin shell with an inclination of 45 using two different layer heights: equal to ¼ of the nozzle diameter and ½ of the nozzle diameter. It can be seen that a low layer causes less overhang of the material during printing, which significantly improves the quality and consistency of the print, and therefore its durability when no supports are used.

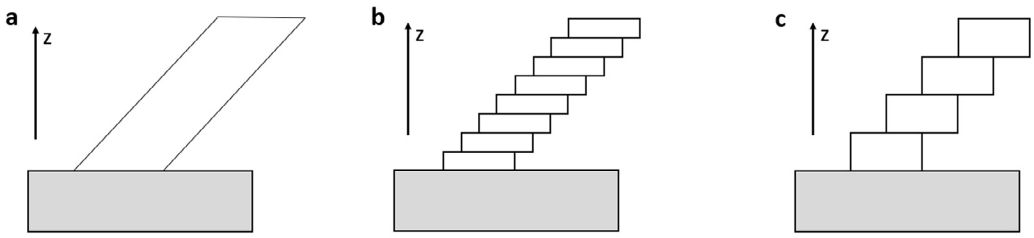

Figure 8. Impact of layer thickness on print quality:
(A) base geometry, (B) print with a layer height of ¼ of the nozzle diameter,
(C) print with a layer height of ½ of the nozzle diameter.

The printout can have the same layer thickness along the entire height, but also a variable layer height can be used to optimize the printing time: low layers in areas of large tilts and geometry changes, and higher layers in areas of small shape variability. Typical slicers offer a constant layer height for the entire print what is a certain limitation.

FDM—Optimal printing paths

The movement of the head always delivers material (no valve present in the printing head) and heat. Therefore, its movement cannot be random or uncontrolled. The entry and exit of the nozzle from the outline of the printed element causes an uncontrolled outflow of molten material in the entry and exit areas. It also provides uncontrolled and spot heat delivery in the re-entry zone (remelting). Therefore, the best paths for high-quality 3D printing are unicursal figures (i.e., those that can be drawn "without taking the hand off"). The printing nozzle path on a given layer can be divided into two paths: for outer surface and for reinforcing structure. Then there is no need to use unicursal paths, but the print quality decreases (Fig. 9).

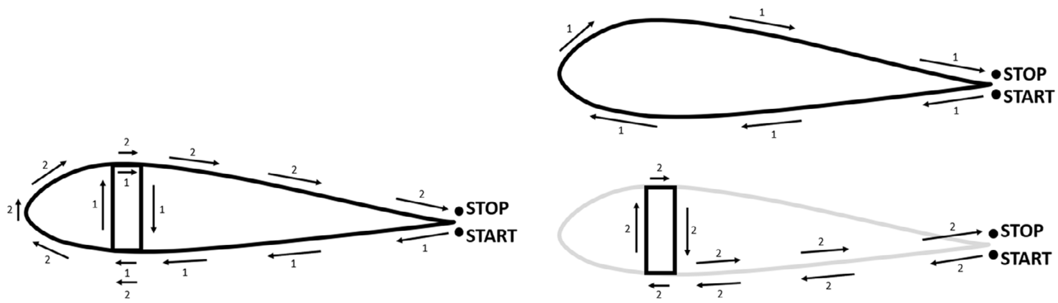

Figure 9. Using unicursal figures to create a path for printing head: on the left – one step printing, on the right – two steps printing: outer contour and inner structure.

Tapered and untapered wing cross section printed with the use of unicursal path is shown in Figure 10.

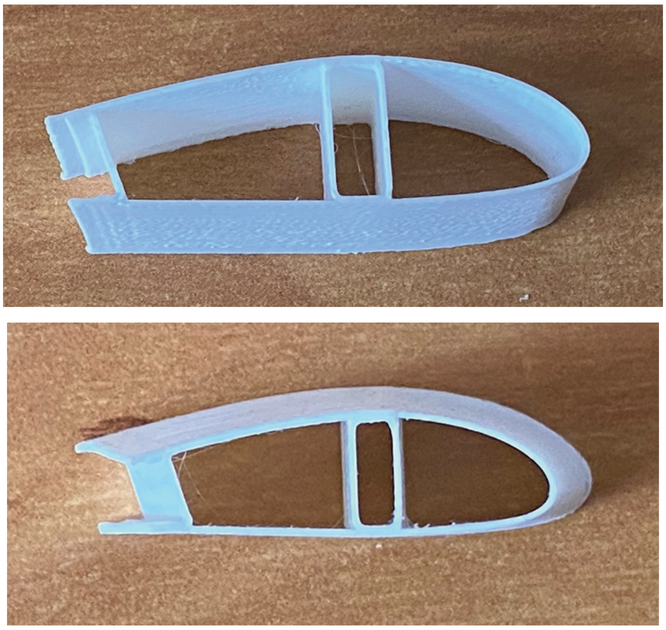

Figure 10. Cross-section of the wing with box and rear spars.

Print segmentation

Every machine tool, including a 3D printer, has a maximum working space. It determines the maximum size of the processed element in the X, Y, and Z directions. FDM 3D printers have a working area most often in a shape similar to a cube; only a few models have a much larger range of the Z axis. This limitation is not significant when producing compact elements with low elongation in every direction. However, it becomes crucial when printing slender elements with high elongation. Elements such as wings and fuselages must be divided into elements that will fit in the printer's working space and then glued together. This requires the use of elements that position and strengthen the connection point. Two solutions for connecting elements were proposed: the first one does not have positioning element, while the second one has it (Fig. 11).

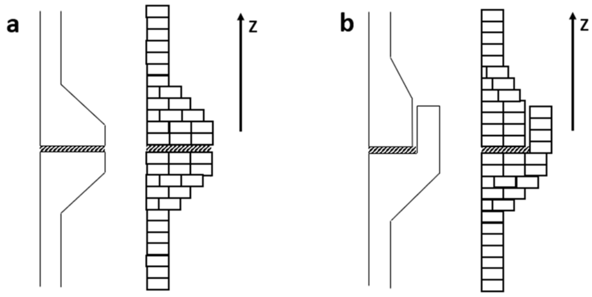

Figure 11. Methods for connecting printed segments with the arrangement of layers marked, (A) without part positioning element, (B) with a positioning collar. Printed wing parts with the positioning collar are shown in Figure 12.

Figure 12. Printed segment of a wing with positioning collar that is used for final assembly.

Longitudinal reinforcement of slender parts

The fuselage is one of two typical slender elements used in the construction of flying models. Longitudinal reinforcing features can be easily made using unicursal paths as well (Fig. 13).

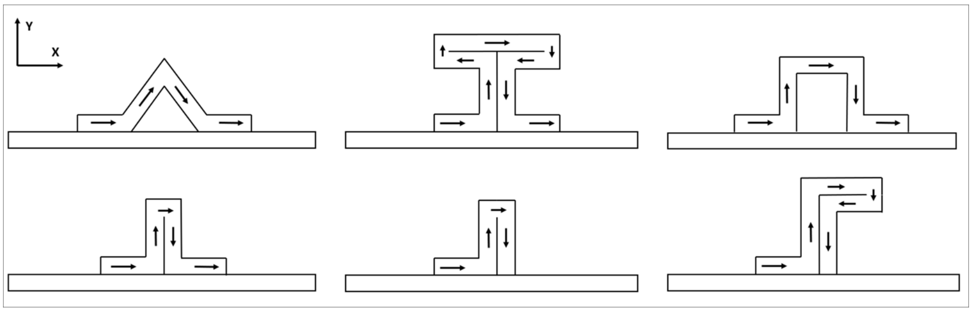

Figure 13. Typical elements used to strengthen the semi-monocoque structure. The arrows indicate the printing direction. The elements are fused into the outer shell with an overlap.

Printed segments of fuselage having strengthening longerons, both tapered and untapered, are shown in Figure 14.

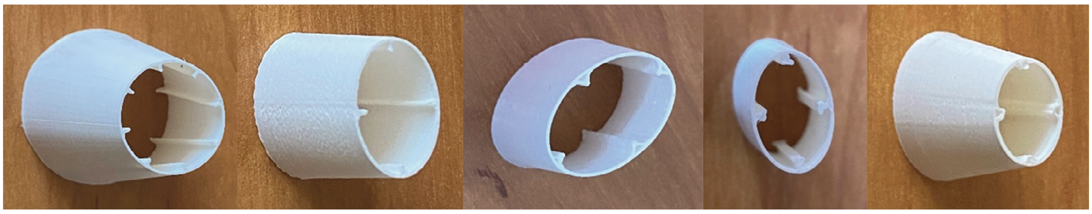

Figure 14. Elements strengthening the fuselage structure.

Supportless printing of ribs and frames

The fuselage and wing need peripheral reinforcements. Elements such as ribs and frames can be made without supports. Such printing involves gradually moving the next layer by a fraction of the shell thickness. If the overhang is small enough, the structure holds the next layers on its own. Owing to this, it is possible to print overhangs with an angle of up to approximately 45 without the need to use supports. Such an overhang can be made on both sides, and thus also return to the initial position. You can also divide printing into two paths: the outer outline track and the overhang track, which will form the rib. Both solutions are shown in Figure 15.

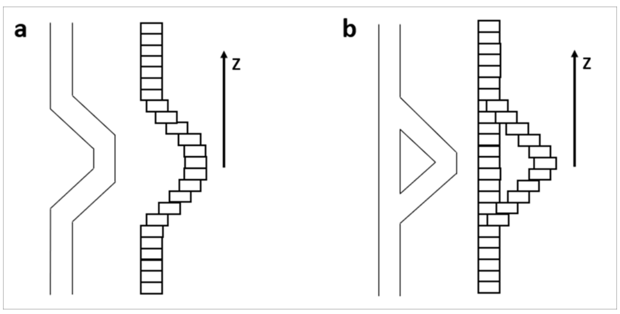

Figure 15. Methods of stiffening the shell, indicating the arrangement of layers, (A) embossment, (B) rib.

Printed segment of a wing with embossment on the leading edge is shown in Figure 16.

Figure 16. Embossing on the leading edge.

Print path crossing

In most cases of the manufacturing techniques, the elements of the structure are separated from each other and are finally put together to create a larger whole. In the case of FDM printing, the printing path (and the manufactured elements) may overlap and interpenetrate. This allows the elements to be melted into one another, thus enabling any thickening of the elements, their mutual connection with each other, and the easy shaping of protruding elements that would normally have to be connected using screws, rivets, or glue. This results in elegant, light, and monolithic structures as shown in Figure 17.

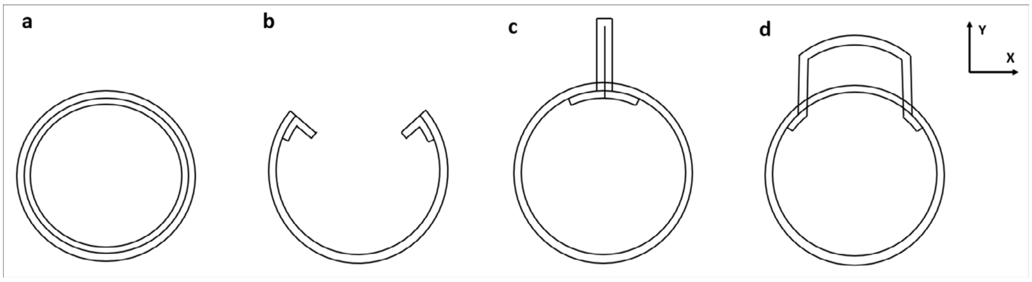

Figure 17. Elements made by interpenetrating the printing path,
(a) – reinforcement ring frame, (b) – edge reinforcement, (c) – external plate or stabilizer,
(d) – external tray or tank.

Using a heatbed for horizontal features

In the printing process, producing all horizontal elements (in the XY plane) is very difficult and basically impossible without supports. The exception is when the material is printed directly on the heat bed (work table). This is the only case when a horizontal element can be made without supports. In the construction of a model, this can be used in two ways: by making a horizontal rib in a wing or fuselage segment (only one per segment) or by making a wing or a vertical tail end plate. Features printed using heat bed as a natural support are presented in Figure 18.

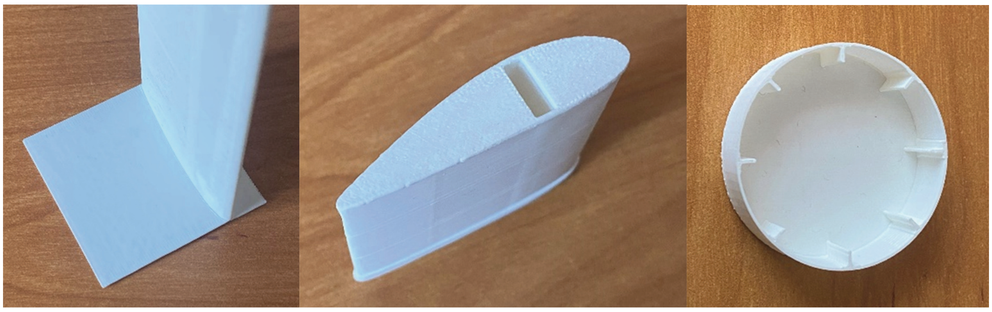

Figure 18. Features created using head bed: wing end plate (left), wing root rib (middle), fuselage bulkhead (right).

Printing problems and defects

3D printing, like any other technology, is not problem-free, and final prints may have defects related to the geometry of the printed element, the way the printing head path goes, and the excessive heat supplied when the head moves. Typical printing failures are presented in Figures 19–22.

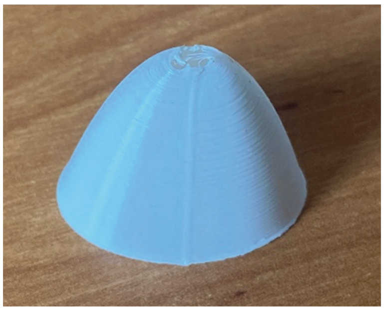

Figure 19. Print defects: limitations for prints without supports and a seam resulting from a temporary stop of the printing head on its path.

Figure 20. Waves caused by the non-extrusion movement of the printing nozzle.

Figure 21. Collapse of the shell caused by the presence of elements reinforcing the semi-monocoque structure.

Figure 22. Melting of the outer surface caused by overheating (e.g., due to too long or frequent stay of the printing nozzle head in the same area).

Materials

Various materials are used in printing, most often with melting temperature in the range of 190–240°C. Some of them require a heated work table to improve adhesion to the substrate in the temperature range of 60–90°C. They come in natural white or gray colors, and some are transparent in nature. The most commonly used ones are dyed in basic colors. The most commonly used are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). PLA is biodegradable and requires a lower operating temperature; it also releases much fewer unfavorable compounds during processing. ABS requires higher temperatures, but it is a compound obtained from the processing of the crude oil. During processing, which takes place at a temperature of approximately 240C, it may release acrylonitrile and other carcinogenic compounds, which is why it is not often used at home. However, it is also characterized by high strength and good impact resistance.

Less popular materials are Nylon for sliding elements, polyethylene (PET) for transparent elements, polypropylene (PP), and high-impact polystyrene (HIPS). The latter is used in printing support elements (it is easy to dissolve) and for printing decorative elements (it has smooth surface). Recently, wood-like materials and elastomers have been introduced, which, although they cause more problems during printing, can be combined with other nonflexible materials when printing on printers with two extruders. This makes possible to produce integrated elastomeric bearings cheaply.

In aviation applications, not only the strength and fatigue properties are important, but also the ratio of the material's strength to its mass (density). A comparison of typical materials used in 3D printers with typical materials used in aviation is shown in Table 1.

Table 1. Typical construction materials including 3D printing polymers. Strength vs. density (https://monroeengineering.com/info-general-guide-tensile-strength.php).

Material	Yield strength/density [kPa m^3 kg^{-1}]
Copper 99.9% Cu	8
Cast Iron 4.5% C, ASTM A-48	18
Brass	23
PLA	29
Steel structural ASTM A36	32
ABS	42
PET	49
Tungsten	49
Steel stainless AISI 302 cold-rolled	63
Chromium-vanadium steel AISI 6150	79
Aluminum alloy 6061-T6	100
Aluminum alloy 2014-T6	148

The strength-to-weight ratio of materials used in 3D printing is in the range of typical construction materials. Additionally, 3D prints made of PLA, ABS, and PET can be reinforced with metal elements (steel, dural, titanium) or composite inserts (glass fiber, carbon fiber, kevlar), which significantly increases the durability of the final structure (while preventing the structure to be completely monolithic). One look on Table 1 shows that polymers used in 3D printing are appropriate for building small aircrafts.

Fatigue strength of 3D printed elements

An important aspect for parts used in aviation is their fatigue strength. Both aircrafts itself and other aviation related parts and systems made of different materials are prone to different kind of fatigue failure (Szafran et al., 2019). Also ground and sea vehicles and their elements, that are produced using aviation technology have to prove their durability and reliability (Szafran et al., 2019, 2021). Aircraft parts practically constantly work under variable loads (propellers, wings, fuselages); therefore, the materials from which they are made must also meet the minimum requirements in terms of fatigue strength.

Although researching polymers is not easy, as experiments may be characterized by a wide spread of results (Ahmadi et al., 2023), many researchers take up this topic and discover interesting facts about these materials. Typical materials such as ABS and PLA differ in fatigue strength to the detriment of the former. A clear influence of the choice of printing direction on fatigue strength was also observed (Azadi et al., 2021), but a positive effect of layer height on fatigue life could not be proven (Travieso-Rodriguez, 2019). The effect of print orientation on the fatigue strength for PLA was estimated to be approximately 25% different depending on the X or Y orientation (Afrose et al., 2016). In turn, in Ezeh & Susmel (2018), it was shown that PLA produced in the FDM printing process has a similar fatigue strength as the same material shaped classically, and that printing parts with filling <100% reduce the fatigue life and behave like a material with a notch. A large impact of the stresses and the existence of a notch on the decrease in high-cycle fatigue strength for PLA was observed (Algarni, 2022). The presence of a notch has a negative impact on this material, reducing the strength of such parts by up to half. The effect of mean stress on fatigue is similar to metal.

The properties of materials used in 3D printing may be different; one of the most interesting is biodegradability, characteristic of PLA. In some applications, such as loitering munitions, this property may be desirable. Work is underway on other biodegradable polymers, including: PLA reinforced with natural fillers. Work (Mueller et al., 2022) shows that the addition of natural components does not adversely affect the fatigue properties of reinforced PLA. It is worth to mention that the areas of risk for fatigue failures are the layers boundaries, as the readymade prints often brake in these regions, Figure 23.

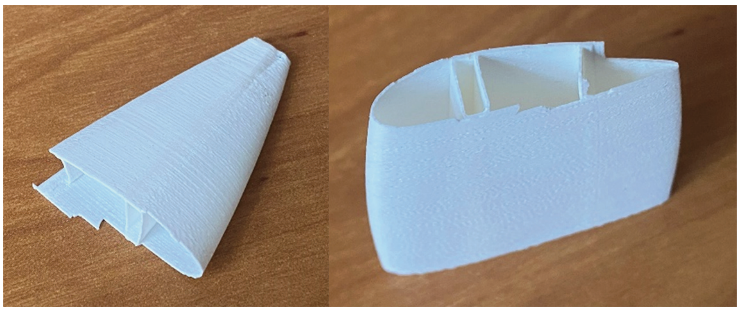

Figure 23. Wing damage: crack at the boundary of layers.

Conclusions

The materials used in 3D printing are suitable for printing small models and drones. Their parameters are sufficient for this purpose. An interesting feature is biodegradability, which is an advantage in aircraft that may be lost during their mission. Fatigue properties also do not disqualify these parts and this technology. As shown in this article, load-bearing elements of flying models can be easily and cheaply shaped using FDM printing, and the use of the proposed fabrication techniques makes the use of supports and additional mechanical processing of these parts largely unnecessary. However, to obtain a cheap, durable, and high-quality product, one need to pay special attention to the method of layering, printing speed, shaping the tool path, and the appropriate selection of material. For this reason, the use of typical, nonspecialized software to create programs for FDM 3D printers appears to be unjustified and burdened with many drawbacks. Each part-production technology has its own specificity and must be taken into account in the production process.

References

Afrose, M. F., Masood, S. H., Iovenitti, P., Nikzad, M., & Sbarski, I. (2016). Effects of part build orientations on fatigue behaviour of FDM-processed PLA material. *Progress in Additive Manufacturing*, *1*(1-2), 21–28. https://doi.org/10.1007/s40964-015-0002-3

Ahmadi, R., D'Andrea, D., & Santonocito, D. (2023). Fatigue assessment of 3D-printed porous PLA-based scaffold structures by Thermographic Methods. *IOP Conference Series: Materials Science and Engineering*, *1275*(1), 012002. https://doi.org/10.1088/1757-899x/1275/1/012002

Algarni, M. (2022). Fatigue behavior of PLA material and the effects of mean stress and notch: Experiments and modeling. *Procedia Structural Integrity*, *37*, 676–683. https://doi.org/10.1016/j.prostr.2022.01.137

Azadi, M., Dadashi, A., Dezianian, S., Kianifar, M., Torkaman, S., & Chiyani, M. (2021). High-cycle bending fatigue properties of additive-manufactured ABS and PLA polymers fabricated by fused deposition modeling 3D-printing. *Forces in Mechanics*, *3*, 100016. https://doi.org/10.1016/j.finmec.2021.100016

Ezeh, O. H., & Susmel, L. (2018). On the fatigue strength of 3D-printed polylactide (PLA). *Procedia Structural Integrity*, *9*, 29–36. https://doi.org/10.1016/j.prostr.2018.06.007

France, A. K. (2014). *Świat druku 3D. Przewodnik. Kompedium wiedzy o druku SD* [*Make 3D Printing. The Essential Guide to 3D Printers*]. Helion.

Guide to Tensile Strength | OneMonroe. (n.d.). Home | OneMonroe. Access 26 Nov 2023 https://monroeengineering.com/info-general-guide-tensile-strength.php

Mueller, M., Sleger, V., Kolar, V., Hromasova, M., Pis, D., & Mishra, R. K. (2022). Low-cycle fatigue behavior of 3D-printed PLA reinforced with natural filler. *Polymers*, *14*(7), 1301. https://doi.org/10.3390/polym14071301

Szafran, K. S., & Kramarski, I. (2019). Fatigue degradation of the ram-air parachute canopy structure. *Fatigue of Aircraft Structures*, *2019*(11), 103–112. https://doi.org/10.2478/fas-2019-0010

Szafran, K. S., & Michalczyk, M. (2021). Research on hovercraft – fatigue cracks in the engine frame. *Fatigue of Aircraft Structures*, *2021*(13), 106–115. https://doi.org/10.2478/fas-2021-0010

Travieso-Rodriguez, J. A., Jerez-Mesa, R., Llumà, J., Traver-Ramos, O., Gomez-Gras, G., & Roa Rovira, J. J. (2019). Mechanical properties of 3D-printing polylactic acid parts subjected to bending stress and fatigue testing. *Materials*, *12*(23), 3859. https://doi.org/10.3390/ma12233859