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DESIGN AND TESTING OF MULTI-MATERIAL FLEXURE HINGES FOR FUSED FILAMENT FABRICATION

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ABSTRACT: Flexure hinges are non-assemble flexible joints that allow the relative rotation of two adjacent rigid parts through bending. Traditionally thermoplastic material hinges are made through injection moulding. 3D printing technologies such as Fused Filament Fabrication (FFF) introduced new possibilities regarding hinges development due to design freedom and the availability of multiple materials. However, the current state of the art focuses mainly on single materials hinges with non-symmetrical design for one-way folding. For this reason, this paper aimed to identify and test multiple design solutions for two-way folding hinges made of compatible and low-compatible thermoplastic materials using design thinking methods. The design process considered the materials' bond formation, resulting in overlapping designs for compatible materials and interlocking designs for the others. The considered materials were acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) with thermoplastic co-polyesters (TPC) for the hinge. The resulting designs of multi-material two-way folding hinges were tested using a tensile test to evaluate the performance of the interlocking mechanism. The results show that macroscopic interlocking provides the best results.

Keywords: *Flexure hinge; Two-way folding; Fused filament Fabrication, Multi-material; Macroscopic interlocking mechanism*

1. INTRODUCTION

The flexible or compliant mechanisms are systems that use the flexibility of their components to achieve motion. Such components are flexure hinges or living hinges

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(Howell, 2013). A conventional living hinge is generated by starting from a blank piece thinned by one or two cutouts. It results in a thin beam connecting two adjacent bodies, allowing relative rotation between bodies through bending (Liu et al., 2017).

Conventionally, living hinges are made through injection moulding with no assembly required and are single materials designs. Polypropylene (PP) is a material that can exceed one million folding cycles (Balderrama-Armendariz, 2019). Depending on their application, living hinges can have multiple designs, such as simple beams, with transition radiuses or rounded profiles (Figure1).

The development of 3D printing technologies introduced new possibilities regarding part manufacturing (Jandyal et al., 2022), and living hinges design can be one of them. As presented in figure 1, the design solutions refer to non-symmetrical geometries allowing one rotational degree of freedom in one direction (i.e., one-way folding). Even if multiple researchers have studied the behaviour of the same design (figure 1a, c, f) made of the same materials, the results have differed due to the distinct testing methods (Lussenburg et al., 2021). Multi-material 3D printing can introduce new possibilities regarding living hinge designs by using flexible materials only for the bending component. Currently, FFF technology offers the widest variety of materials that can be explored. However, standard multi-material 3D printing uses a head-to-head contact interface for the mating bodies and is limited to materials compatibility.

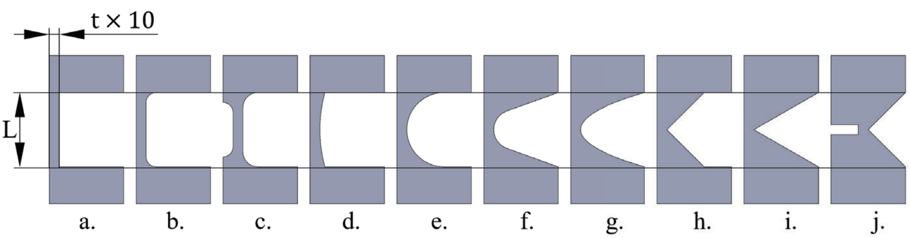


Figure 1. Side view of flexure hinges design with equal hinge thickness (t) and length (L) and different geometries. Adapted from Lussenburg et al., 2021 & Liu et al., 2018.

Ando et al., 2021 and Ermolai et al., 2022 showed that a head-to-head interface would not result in a flat-to-flat bonding profile when printing with FFF technology. Instead, the materials are printed layer-wise, and the materials are zigzagging at the boundary region of the mating bodies. Zones of vertical and horizontal contact characterise the resulting bond. They also concluded that overlapping parts' bodies is necessary to increase bond strength. The overlap provides a design direction for multi-material hinges.

Ribeiro & Carneiro, 2018 investigated the tensile properties of multi-material samples of high-compatible PLA-PLA and low-compatible PLA-TPU materials. They concluded that a standard head-to-head contact interface does not offer good mechanical properties. Therefore, a more robust macroscopic interface is required.

This paper explores the various designs of multi-material hinges for two-way folding made of compatible (i.e., ABS-TPU) and low-compatible (i.e., PLA-TPU) materials. Design thinking methods were used to identify as many solutions as possible (i.e., axiomatic design principles and idea map). A fraction of the resulting hinges concepts were designed as samples in a CAD environment for the FFF 3D printing process. The resulting models were tested using a tensile test to evaluate the performance of the interlocking mechanism. The results show that macroscopic interlocking interfaces provide the best results.

2. METHODS

2.1. Design method

A design methodology was developed consisting of five steps to provide a framework for the design process of the two-way folding hinges. The first two steps establish the hinge design's functional requirements, design parameters, and constraints. These steps are based on the axiomatic design principles developed by Nam Suh (Suh, 2001). Because the axiomatic design method leads to a unique solution, it was considered that, in this case, testing multiple solutions is more beneficial for the aim of this paper. For the third step, the development of an idea map was considered. Finally, the last two steps refer to concept testing and validation. The design steps are as follows: *Step I - Define functional requirements and constraints, Step II - Identify design parameters and process variables, Step III - Create the idea map, Step IV - Prototyping and testing, and Step V - Concept validation*.

The first step was identifying the hinges' functional requirements and design constraints based on customer needs (i.e., researchers). Secondly, those were redefined as design parameters with their process variables. The resulting design matrix for the multi-material two-way folding hinges is presented in figure 2.

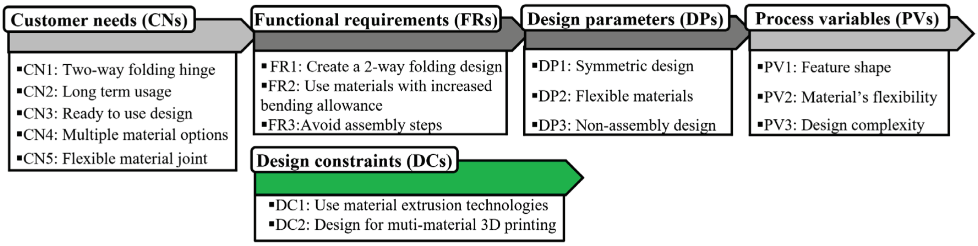


Figure 2. Definition of functional requirements and constraints.

The idea map was defined in the third step of the ideation process. It consists of two design directions: the flexible hinge geometry and the multi-material interlocking mechanism (figure 3). Regarding the flexible hinge design, the most convenient solution was to adapt the design of the existing hinges (figure 1) to the two-way folding requirement. Besides this, the development of new hinge designs was considered. The solutions are profiles based on regular hinges and shape morphing structures, which can change their 2D shape into a 3D shape under plastic deformation (Wu et al., 2022). In addition, possible morphing designs can be based on corrugated and auxetic structures (see figure 3). However, these solutions are limited to material compatibility. The bonding mechanism depends on mating bodies' interface contact area size and the materials' chemical adhesion. Macroscopic (geometrical) interfaces between the hinge's body and mating elements were considered to compensate for those limitations. This approach can be used for both material groups, compatible and low-compatible.

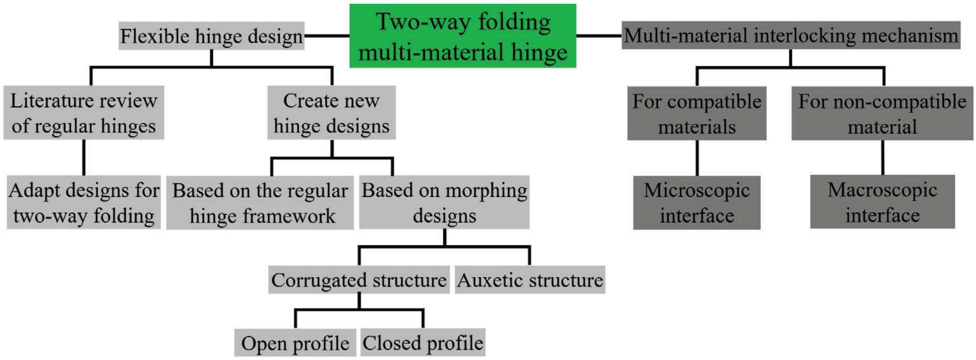


Figure 3. The idea map of the multi-material two-way folding hinges.

In this study, only a fraction of the identified hinges solutions from the idea map were considered for testing. Those are adapted profiles and new geometries based on existing hinges (i.e., from figure 1). Furthermore, microscopic and macroscopic interfaces were studied for the multi-material interlocking mechanism.

Based on those mentioned above, two testing groups were considered. The first group consists of the adapted regular hinges and the second with an interlocking mechanism. Those were designed for compatible thermoplastic materials (i.e., ABS and TPU). The second group with the new hinges designs combined the microscopic interlocking mechanism. Their behaviour was tested for compatible and low-compatibility materials (i.e., PLA and TPU).

2.2. Specimens and contact design

As for the design consideration, based on DC1 and DC2 (figure 2), all models were drawn based on the DfAM rules (i.e., Design for Additive Manufacturing). All models were designed for FFF 3D printing with a 0.4 mm nozzle.

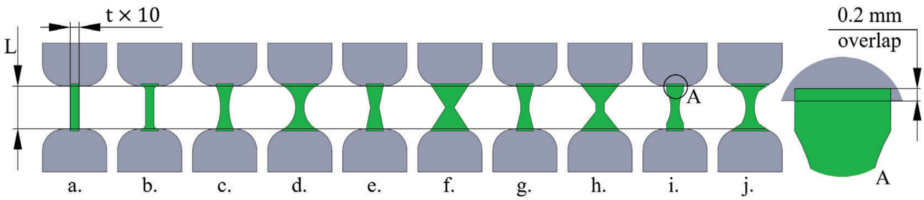


Figure 4. Side view of hinges based on (figure 1) adapted for two-way folding: a. rectangular profile, b. rectangular profile with transition radius, c. narrow hyperbolic profile, d. wide hyperbolic profile, e. narrow hourglass profile, f. wide hourglass profile, g. combined narrow profile (a&e), h. combined wide profile (a&f), i. combined narrow profile (a&c), j. combined wide profile (d&f).

Ten adapted profiles resulted based on regular hinge profiles (figure 1). Their shape varies from a rectangular shape (figure 4a, b) to a hyperbolic shape (figure 4c, d) to an "hourglass" profile (figure 4e, f) or combinations of them (figure 4g-j). The basic dimensions were hinge length L (i.e., 4mm) and thickness t (i.e., 0.8 mm). The remaining unquoted sizes were constrained with linear dimensions as multiples of 0.4 mm (i.e., nozzle diameter). Based on the findings of Ando et al., 2021 and Ermolai et al., 2022 , a constructive overlap was designed between the flexible hinge and mating bodies (detail A of figure 4).

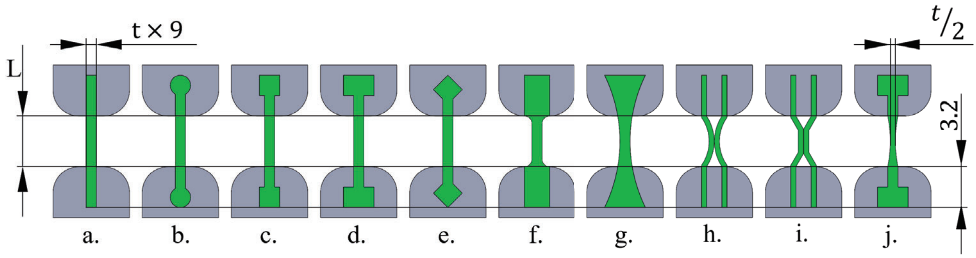


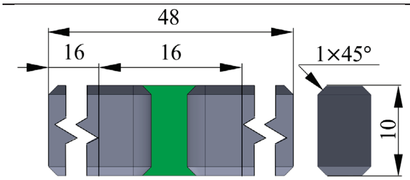
Figure 5 – Side view of the design of the new hinges based on regular profiles with a macroscopic interlocking interface: a. straight rectangular profile, b. rectangular profile with circular ends, c. rectangular profile with square ends, d. rectangular profile with rectangle ends, e. rectangular profile with rhomboid ends, f. rectangular profile with transitory ends, g. hyperbolic profile, h. biconcave circular profile, i. biconcave hexagonal profile, j. necked rectangular profile with a rectangular end.

The second group of hinges consists of 10 geometry designs. Six are based on rectangular profiles with various ends for the interlocking geometry, such as circle, square, rectangle, and rhomboid (figure 5a-f). Other designed profiles were hyperbolic with the wider region as an interlocking geometry (figure 5g), biconcave circular profile (figure 5h), and biconcave hexagonal profile (figure 5i), both with straight ends. The last considered profile (figure 5j) is based on figure 5d but with a thining in the midzone.

2.3. Printing process parametrisation

Two materials were chosen for the specimens' bodies, a dark-grey PLA from 3Dimensionals and a light-grey ABS from REC. As for the hinge, a green Innoflex 45D TPC material from BASF was selected. The printing files were generated using Cura 4.13.0 and printed on an Ultimaker 3 3D printer. Each design configuration was printed with four replicates with the same setup regarding geometrical specifications (e.g., layer height, number of walls). All considered settings are shown in table 1.

Table 1. Print process parameters



Abbreviations:
- extr. - extrusion;
- temp. - temperature;
- spd. - speed;
- dist. – distance;
- thk. – thickness;
- no. - number.

Values in Italic refer to ABS material;
Values in Bold refer to TPC material.

Parameter	PLA/*ABS*/**TPC**	Parameter	Value
Extr. temp. (°C)	215/*245*/**240**	Layer thk. (mm)	0.15
Bed temp. (°C)	60/*90*/**60**	Extr. width (mm)	0.4
Print spd. (mm/s)	30/30/**5**	No. of perimeters	3
1st layer spd. (mm/s)	15/*15*/**5**	No. of top/bottom layers	6
Retraction dist. (mm)	7/*7*/**4**	Infill pattern	Gyroid
Retraction spd. (mm/s)	35/*35*/**40**	Infill density (%)	10
Fan spd. (%)	100/*0*/**25**	Brim	Yes
Closed environment	No/*Yes*/**No**	Brim width (mm)	3

3. Result and discussion

All samples were tested for tensile strength using an Instron 4411 universal machine at 10 mm/s speed. The laboratory conditions were 22.5°C with 39% humidity. The average results were used to evaluate the hinges design and the interlocking mechanism.

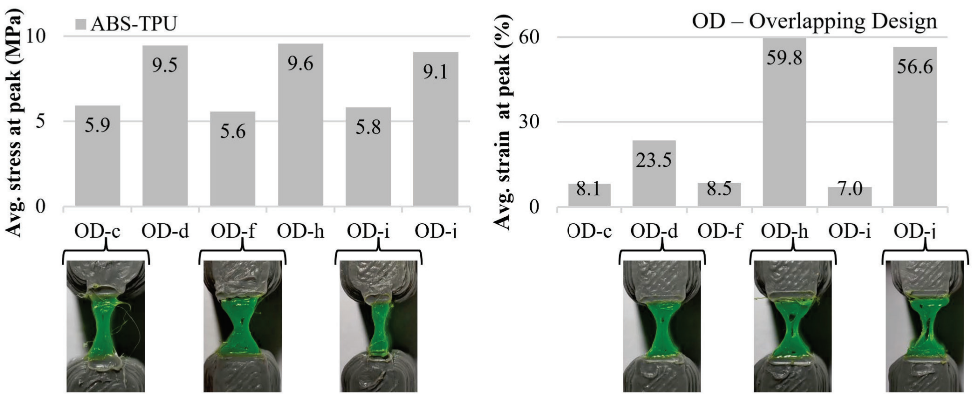


Figure 6. Average stress and strain for the overlapping design hinges.

Only a part of the printed samples of hinges with overlapping designs was tested for contact interface bond strength. Due to the poor bond formation between the ABS and TPC materials, only c, d, f, h, i, and j designs were tested (figure 4). It can be observed that the bonding mechanism is influenced by the size of the interface surface between the hinge and mating bodies. Thus, the vertical and horizontal adhesion areas are affected by interface size. Regarding stress and strain, designs with a wider contact interface had the best results under static load conditions (figure 6, designs d, h, and j). The h design achieved the highest tensile strength, characterised by a wide "hourglass" body and a narrow square region of 0.8 mm. Based on the print result and tensile tests, a rule of thumb can be followed in future work. For multi-material 3D printing, the overlapping design is recommended only for the product that does not require high load capacity. In addition, a minimum interface size should be considered (e.g., a minimum of 1.2 mm in width).

Compared to the overlapping design, the print result had no bonding issue due to the macroscopic interface for the interlocking design hinges. However, a behaviour difference regarding the failure mode was observed between the PLA-TPC and ABS-TPC configurations. After reaching the peak, the TPC hinge split into multiple strings for samples with the PLA body stress. As for specimens with ABS bodies, the hinge body maintained its structural integrity, delaminating only near the ABS mating body. This behaviour was observed for all tested models. The printing conditions can explain the different failure behaviour of the hinge among PLA-TPC and ABS-TPC samples. Because the ABS is sensitive to temperature changes, a closed environment was required. Therefore, it is assumed that the constant environment temperature of 45°C during printing increased the layers fuse between TPC layers. An example of TPC hinge failure behaviour for ID-e design is presented in figure 7 for both materials configurations. Moreover, it can be observed that the tensile strength increases due to the layer's better fuse.

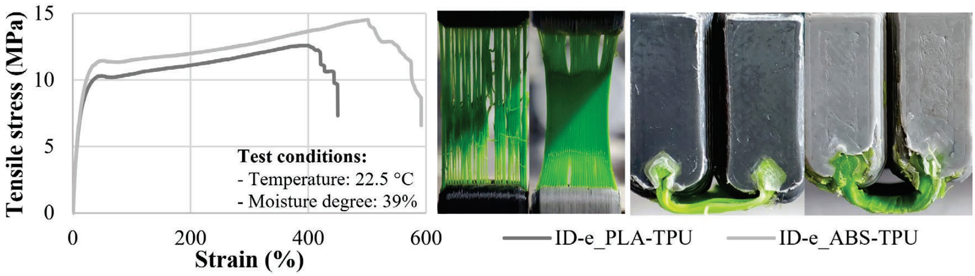


Figure 7. Stress-strain diagram of ID-e hinge design for PLA-TPC and ABS-TPC materials configurations, failure mode at peak and folding results (from left to right).

According to the average test results (figure 8), hinges with the macroscopic interlocking interface showed a considerable increase in tensile stress and strain compared to the overlapping hinge designs. The hinge designs ID-a to ID-f showed comparable results regarding the load capacity but significant differences referring to strain. The best-resulting design was ID-d with 12.6 MPa tensile strength and 684.9 % elongation for the PLA-TPC configuration. For the second group of materials, ABS-TPC, the same design registered 13.9 MPa tensile strength and 619.4 % strain on average. Interestingly, for the same design, by performing a thinning on the hinge design (i.e., ID-j) along with a closed environment during printing, the tensile strength increased to 18.2 MPa with 660.6% elongation. The hyperbolic profile achieved the best performance of the other tested designs, with 14.5 MPa tensile strength and 364.4 % elongation for PLA-TPC and 14.5 MPa strength with 497.3% strain for ABS-TPC. Overall, the best results were obtained for the ID-j hinge printed with ABS-TPC.

Another possible variable responsible for the different behaviour of each hinge design under testing is the travel path during the material deposition. Depending on the feature shape (i.e., the hinge), each contour's starting and closing point can act as a tension concentrator because of the inconsistent amount of deposited material. For example, consider the Seam Alignment parameter (which controls the closing point location) with the Sharpest corner option. For the ID-b design composed of a rectangular beam and two circular profile ends, the sharpest corner is at the intersection between the two profiles. The Seam Alinement setting brings the weld line closer to the outer surface of the hinges' mating body. On the other hand, for the ID-c design constructed using the same beam profile but with two square ends, the sharpest corner identified by the slicing tool is an edge inside the hinge's body. Comparing the test results from the mentioned design, it can be considered that the tool path can significantly influence the multi-material hinges.

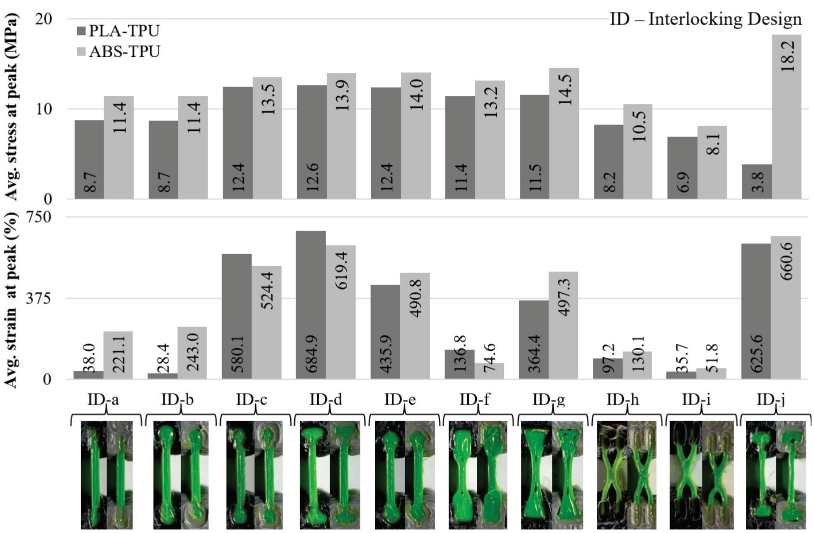


Figure 8. Average tensile strength and strain for the interlocking design hinges.

4. CONCLUSIONS

Multi-material FFF 3D printing offers new possibilities regarding flexure hinge designs. The use of flexible hinge materials allows both one-way and two-way folding hinges. It was shown that multi-material hinges could be made in configurations of compatible and non-compatible materials. The first configuration can achieve good results if there is enough contact surface between mating bodies. However, the resulting bonds between materials lack strength for functional applications. Even with an increased overlap between hinges' bodies, some printed samples could not be tested due to improper bond formation.

On the other hand, the hinges with a macroscopic interlocking mechanism design showed an increased performance compared to the previous designs. It was shown that the printing conditions of the specimens could influence the failure mode of the flexible hinges. A closed printing environment increases layers fuse. Regarding the hinge's design, performing a thinning of the profile in the mid-region can improve load capacity and failure behaviour.

Conflict of interests

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

E.V. conceived, designed, and performed experiments, analysed the results, and wrote the manuscript S.A. and N.G. analysed the experiments, technical proof of results, and reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

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