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FOLDING ENDURANCE APPRAISAL FOR THERMOPLASTIC MATERIALS PRINTED IN FUSION DEPOSITION TECHNOLOGY

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Abstract

The anisotropic behavior of the fusion deposition modeling (FDM) machines could change the mechanical properties of the materials in the layer by layer technology. In general, the tensile, compressive and flexural strength are decreased against molded plastics. Some lasting products need the iteration of low flexural strength and high elongation to obtain an effective flexibility to bend in repetitive movements. The present work provides an analysis of the capacity of several selected thermoplastics materials such as Nylon (PA), Polyethylene Terephthalate (PETG), Polylactide (PLA), Polyurethane (TPU) and Polypropylene (PP) in order to test the maximal load capacity and the number of folding cycles sustained in perpendicular direction of movement. Results demonstrate that those of similar to injected molded products, PP and TPU materials surpass one million of cycles in the folding test. Yet, in axial load they have lower strength against the other considered materials.

Key Words: Folding Endurance; 3D Printing; Fusion Deposition Modeling

Introduction

Flexible materials for Additive Manufacturing (AM) have been used by designers to develop novel textile structures [1] that can be converted in wearable products such as clothes, bracelets, neckless or shoes, while flexible mechanical parts can be printed in the shape of coil, leaf or torsion springs. 3D printed flexible electronics [2,3] are gaining terrain to produce flexible formats that are difficult or impossible to achieve with current technologies [4]. The field is so wide that new business models have been born to solve personalized needs to produce flexible orthoses [5]. Living hinges are printed from simple plastic boxes, to functional articulations for prosthesis [6], robotic hands [7,8] or soft robots [9,10].

FDM is one of the most used technologies in AM. Both, low cost FDM machines and the variety of filaments give new possibilities to create faster prototypes and new product development. Due to the opportunity of AM to print complicated shapes with no need of assemblies, the characterization of the FDM printed components is required. Many efforts to find mechanical properties have been restricted since the anisotropic behavior of the process; however, researchers in the area have evaluated mechanical tensile [11] and compressive strength [12], flexure force [13] and impact [14], but not the property to fold in repetitive cycles.

Folding endurance is defined as the number of folds that are required to make a test piece break under standardized conditions [15]. Standard test methods are applicable to paper of thicknesses up to 0,25 mm thick [15,16]. There are no specific formulas that calculate a folding rate of plastics and no data sheets is proportioned by suppliers. Most commonly injected molding living hinges are made of PP, which can surpass 1 million of folding cycles [17] and a maximum load up to 20 Pounds/in [18]. Other materials used in folding injected molding products are: Polyvinyl Chloride (PVC), Urethane (UR) and PETG.

Process

Five 3D printing filaments were selected with different flexural strength and high elongation to obtain an effective flexibility from bending in repetitive movements: Nylon 12 (Stratasys, Ltd., Eden Prarie, MN, USA), PETG, PLA, PP (Gizmo Dorks, Temple City, CA, USA), and TPU Ninjaflex (NinjaTek, Manheim, PA, USA).

An especial design for specimens was developed due that no standard test for plastic was appropriate for the objectives; transition heat factor provoked by the folding speed was not desirable, thus a folding endurance test for paper (ASTM-D2176-97a; ISO 5626:1993) was discarded. A living hinge design occurred to be the best option found to perform folding test. First prototypes were development according with both the injected molding recommendations and the tool cooling living hinges [19] but the geometries and dimensions did not work for the FDM technology. Instead, applying all the recommendations from a design based on Smyth (2015) [20], a simple created design achieved favorable results (Fig. 1).

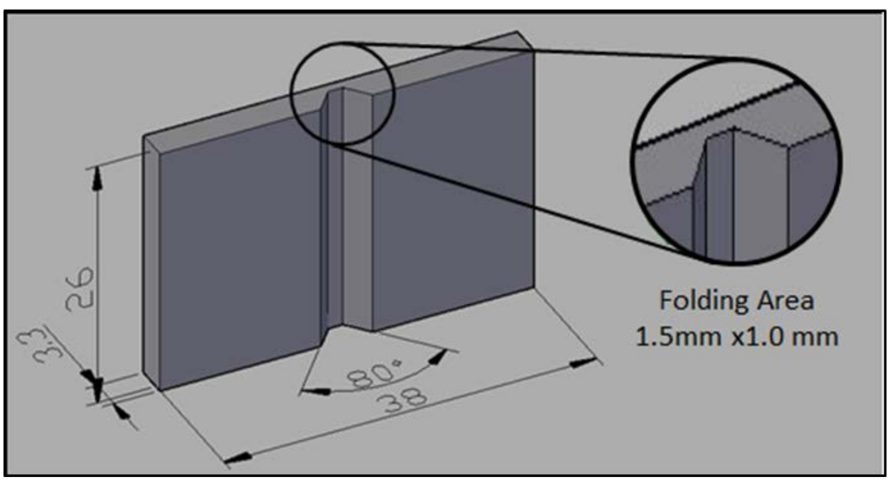

Fig. 1 Living Hinge Specimen

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Living hinges endurance was found by the accomplishment of the following two main tests:

Test 1. Folding Endurance

A control station (Fig. 2) was built it with Arduino UNO (Arduino LLC) and 4 servomotors (JR ST47BB, Champaign, IL,USA) working at 2.22 times per second. Hinges were grasped with special holders and tighten with screws. The center of rotation of motor is aligned with the center of the folding area of the hinge. Controller was programmed to count the cycles of servomotors with 180 degrees of rotation, torque of 47 oz/in and automatic stops when the half of the hinge is fully detached. Nylon Specimens were printed on Stratasys Fortus 400mc (Stratasys, Ltd., Eden Prarie, MN, USA) and other materials in MakerBot Replicator Dual (MakerBot Industries, Brooklyn, NY, USA). Specimens were previously bent by 10 cycles at a temperature of 80°C to give orientation to the fibers according with the folding movement.

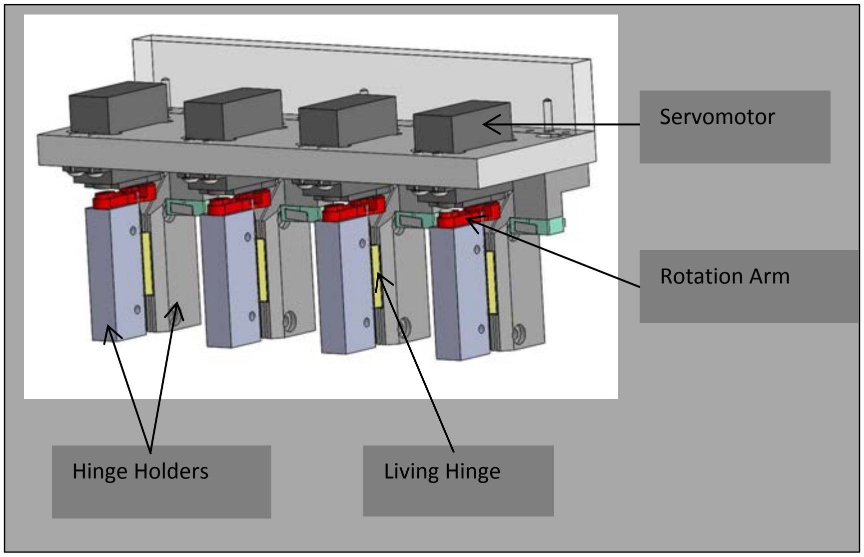


Fig. 2 Control Station for Folding Endurance Test

Test 2 Static Axial Loads

Specimens were attached in two fixtures fabricated for the specimen dimensions (Fig. 3). The Maximum Load Test consisted in measure the pressure with force gauge (Lutron FG-5100, Lutron Electronic Enterprise CO., LTD.) applied with a load cell (100 kgf) in axial direction in two different points listed below:

1. When the specimen starts to have a vertical movement below 100 microns. The goal is to find the maximum point when material starts its plastic deformation and is capable to carry weight with no affection in the precision of the folding movement.
2. When the specimen endures its maximum load until the break point, resulting to obtain the maximum load that the material can support.

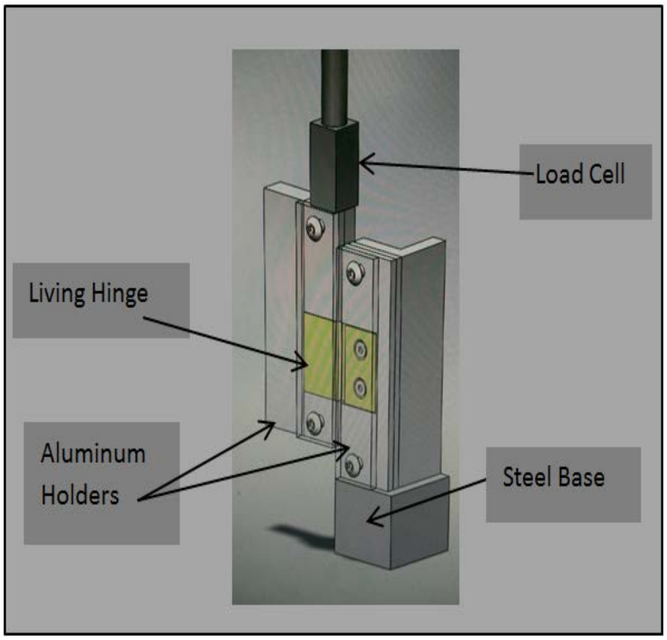


Fig. 3 Static Axial Load

Previous Experiment

By avoiding the anisotropic behavior of the printed parts, an experiment was performed before the programmed tests to find the correct orientation of the printed specimens as well as to know the appropriated raster angle to get the maximum folding cycles. Following the criteria that orthogonal direction of the movement gets better strength, both XYZ and XZY [21] orientations were used. In the case of raster angles, a 0^{o} and $45^{o}/-45^{o}$ were also considered. Fig. 4 represents viewpoints of the orientation of hinges and the direction of rasters. For rapid results PLA specimens were tested with printing parameters fixed deliberately at 0.25 mm of layer thickness with zero airgap, and two shells and 100% of infill. PLA specimens were printed individually and not only heated at 80 C^{o} but also folded 10 times before the experiment took place.

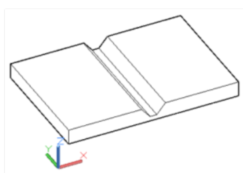
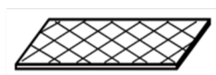
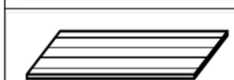
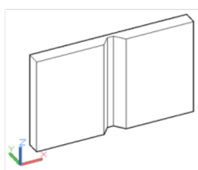
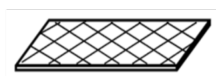
Orientation	Raster Angle	Replicas			$\bar{x}$	S
		1	2	3		
		# Cycles				
		210	196	185	**197**	**12.53**
		220	200	205	**208.3**	**10.41**
		97	107	113	**105.7**	**8.08**
		140	165	129	**144.7**	**18.45**

Fig. 4 Representation of the Hinges and Initial Data of Previous Experiment

Results

The number of cycles obtained in PLA for the previous experiment denoted no significant difference in the direction of the raster angle (0^{o} or $45^{o}/-45^{o}$), but was not the case to those of the 2 types of orientation (Fig. 5); particularly between the two factors used in the XYZ orientation, and the $45^{o}/-45^{o}$ raster angle used in XZY orientation. For subsequent tests, the XYZ orientation with the 0^{o} raster angle with the highest mean (208.3 cycles) were utilized in the specimens volume of test criteria (1.5mm of length, 1mm of width and 25mm of height).

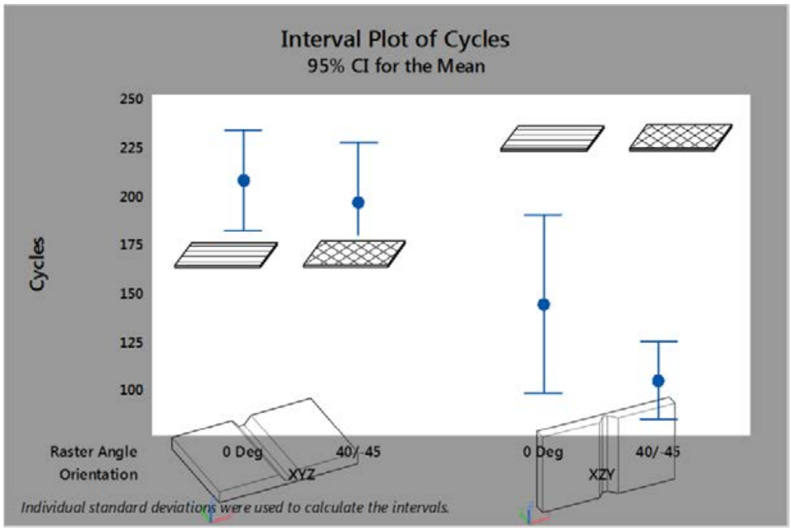


Fig. 5 Plot of Folding Cycles in Previous Experiment

Test 1

For the folding endurance test, PLA and Nylon specimens showed folding cycles below the 200 cycles in their means values, $\bar{x}$ (163.20 and 198.80 respectively) and PETG specimens broke before 900 cycles ($\bar{x}$=856.60, s=92.58). PP and TPU counted cycles resulted with an extraordinary differences among other materials. PP cycles raised more than 1 million whereas TPU test was stopped in 2 million, posteriorly, the specimens were physically checked and no damage in the surface of the folding area was observed. The results are tabulated in Table 1 and a Bonferroni differences are represented in Fig. 6. Despite that the number of cycles of PETG is larger in comparison with PLA and Nylon, no differences are denoted due to manly means of PP and TPU are very large.

Table 1. Tabularized Folding Endurance Test. Results are in the number of cycles completed by different materials

SPECIMEN	MATERIAL				
	PET (cycles)	PLA (cycles)	PP (cycles)	TPU (cycles)	NYLON (cycles)
1	733	136	1130002	+2000000	192
2	920	152	980520	+2000000	126
3	960	172	1107713	+2000000	170
4	876	211	1080536	+2000000	276
5	794	145	1060870	+2000000	230
Mean	856.60	163.20	1071928.20	+2000000	198.80
Std Dev	92.58	29.83	57456.41	0.00	57.25

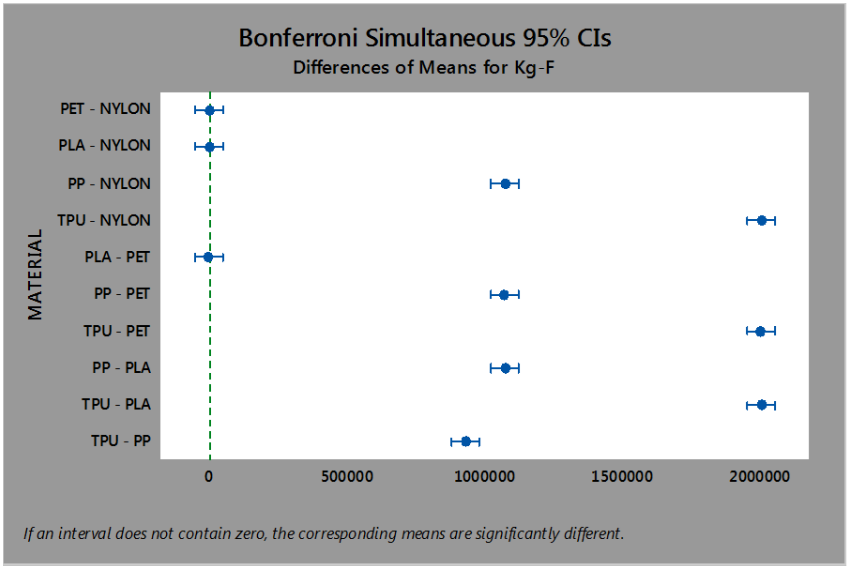


Fig. 6 Bonferroni Differences Analysis in the Folding Endurance Test

Test 2

Axial loads were applied in perpendicular direction of the raster angle where most of the complete sets of hinges were broken in the area of test, but TPU, which in this case, printed rasters got broken in a different part of the hinge (Fig. 7).

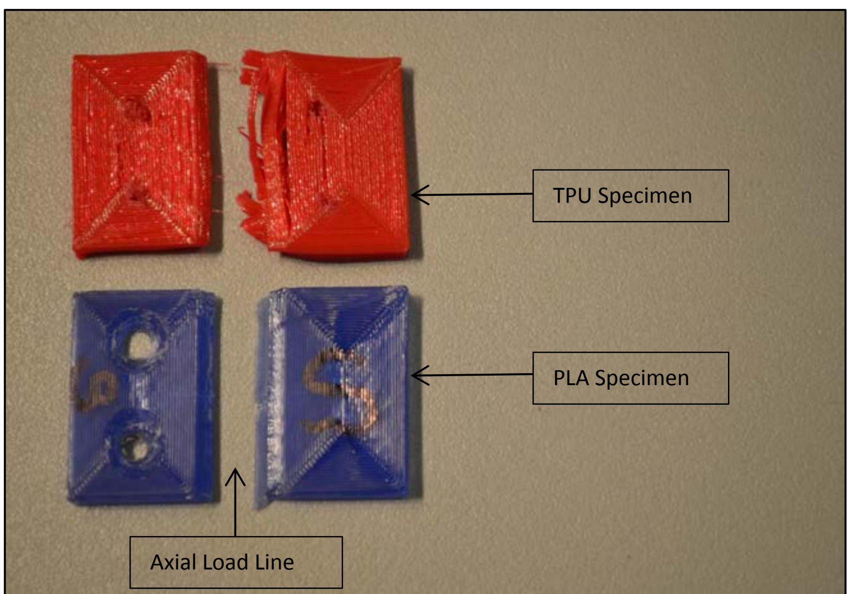


Fig. 7 Differences in the Broken Line between TPU and PLA Specimens

Table 2 shows the data obtained in two points of the test: i) the applied force before a plastic deformation in the specimen and ii) the maximum load applied until the hinge is broken. Greater variability is observed in TPU and Nylon thermoplastics. In the case of TPU, results differ from overall mean that were observed (Fig. 8). With the exception of TPU material, large variability is presented in all samples tested, taking only 0.59 kgf to move TPU hinge in axial direction against the 6.86 kgf of the PET specimens.

Table 2. Results of Axial Load Test in Five Materials in Two Different Points of the Test

SPECIMEN	MATERIAL									
	PET (kgf)		PLA (kgf)		PP (kgf)		TPU (kgf)		NYLON (kgf)	
	Before Deformation	Maximum Load	Before Deformation	Maximum Load	Before Deformation	Maximum Load	Before Deformation	Maximum Load	Before Deformation	Maximum Load
1	8.60	69.85	7.45	70.25	3.75	25.05	1.05	35.40	9.40	67.01
2	8.55	67.05	4.10	83.60	5.30	27.35	0.50	24.00	4.20	60.70
3	5.30	67.30	8.15	81.30	3.60	32.20	0.55	19.55	7.40	62.70
4	6.30	64.05	6.60	82.80	5.20	33.60	0.45	30.10	7.45	76.80
5	5.55	66.25	5.20	85.15	5.65	31.35	0.40	27.25	4.35	65.60
Mean	6.86	66.90	6.30	80.62	4.70	29.91	0.59	27.26	6.56	66.56
Std Dev	1.61	2.09	1.65	5.96	0.95	3.57	0.26	6.01	2.24	6.23

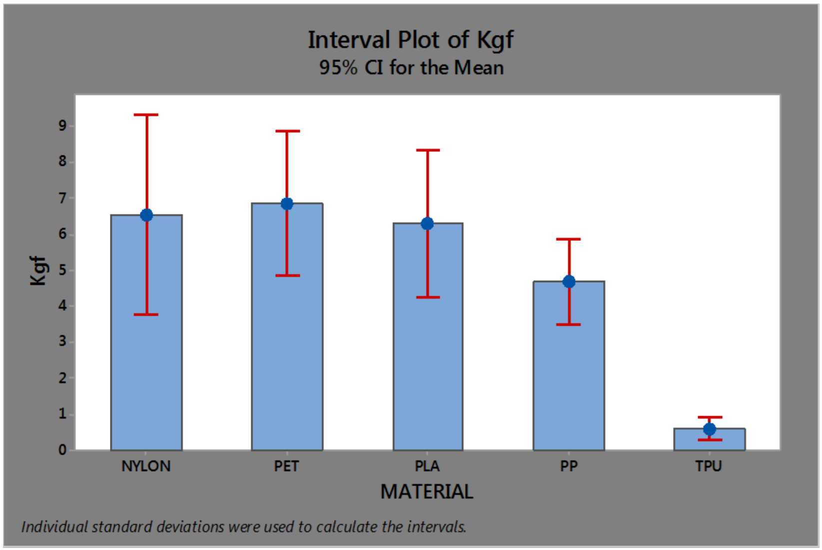


Fig. 8 Interval Plot for the Response of Axial Force before any Deformation Occurs

Interval plot of the Maximum Load is presented in Fig. 9. Here the difference is notable between the hard and the elastic materials. PP and TPU have no significant differences in the test before deformation process. Bonferroni simultaneous test confirms this as it is shown in Fig. 10, where an overlap can be seen with standard deviations of PET and Nylon. Also, PLA occurs to have the highest level of strength against axial load showing a statistic difference with PET and Nylon.

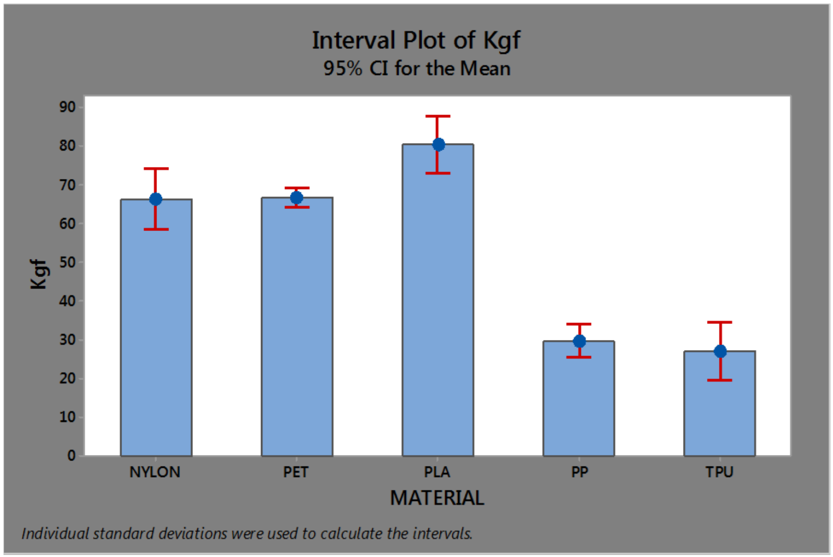


Fig. 9 Interval Plot for the Response of Axial Force to a Maximum Load

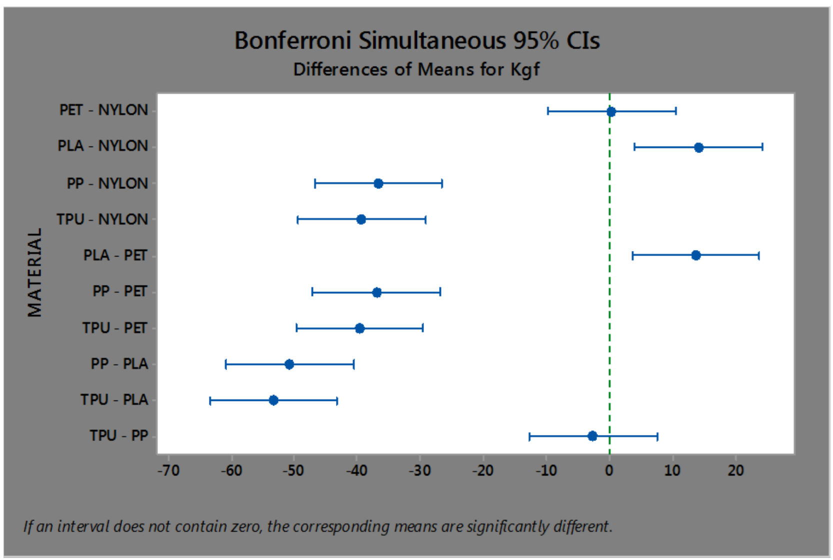


Fig. 10 Bonferroni Differences Analysis in the Axial Maximum Load

Conclusions

Thermoplastics materials used as filaments for fusion deposition modeling can be used in the manufacture of folding products for diverse applications. PLA and Nylon materials result suitable for rapid prototyping of a few cycles folding objects, or for the rapid manufacture of non-lasting folding products like packaging, that support a good level to sustain adequately axial forces nearby 6 kg with no deformation. PETG occurs to work at 800 cycles above and with a 180° folding angular displacement, and an arithmetic mean that holds a static weight of 6.86 kgf, where the maximum load endurance mean resulted to be 66.90 kgf.

PP semi-rigid material can behave as good as some folding injected molded products made by PP with an ability to be fold over 1 million of cycles. In the axial load test, PP was observed to be statistically similar to those of more rigid materials mentioned in above paragraph. TPU formulated thermoplastic (NinjaFlex Brand) was tested for 2 million of folding cycles with no visual damage. Yet, TPU could be used for applications with low strength to axial loads or designs with TPU inserts combined with other rigid materials.

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