TITLE

Development of a 2-axis compliant joint for the orientation of payloads on small satellites: Material characterization and finite element analysis of 3D printed PolyEtherKetoneKetone (PEKK) and PolyEtherEtherKetone (PEEK)

ABSTRACT

In this study, a 2-axis joint of ± 45° rotation range per axis is developed to orient payloads such as cameras, antennas or sensors on small satellites. It is a polymer-based 3D printed compliant mechanism, meaning that the elastic deformation of its intricate structure is used to create complex movements. Two high-temperature polymers printed using Fused Filament Fabrication (FFF), PolyEtherKetoneKetone (PEKK) and PolyEtherEtherKetone (PEEK), are chosen for this work. First, the study aims at selecting the best performing of the two 3D printed polymers through material characterization. Then, focusing on a section of the joint, the cross-axis flexural pivot, the previous results are used to develop a finite element analysis that accurately models its mechanical behavior. Mechanical and thermal characterization are performed through Differential Scanning Calorimetry (DSC), tensile and flexural tests. The model uses the results from tensile tests and compares the displacements generated by the application of a force on the joint. Finally, the mechanical behavior of 3D printed cross-axis flexural pivots is compared to their numerical twin thanks to image correlation. The finite element analysis will be developed further for future works to study more complex mechanical behaviors such as vibration response.

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KEYWORDS

Fused Filament Fabrication, Poly(EtherEtherKetone), Finite element analysis, Mechanical Properties

1) Introduction

To extend opportunities for small satellite buses to individually adapt the orientation of their payloads while expanding their visual range, a 2-axis polymer-based joint of ± 45° rotation range per axis is in development [1]. To ensure precise motions and accuracy of the oriented payloads, such as cameras, antennas or sensors, the joint is composed of a monolithic, compliant mechanism instead of a traditional assembly of parts. Indeed, the joint presented in this study only uses the elastic deformation of its structure composed of cross-axis pivots to create complex movements. Consequently, it is not subject to wear or backlash, and it does not need lubrication. These qualities make an adequate candidate for space applications [2]. Compliant mechanisms like the one presented in this study can have intricate structures. Therefore, 3D printing is the process chosen to produce this joint, despite concerns over the decrease of mechanical properties of 3D printed parts over other processes [3], [4] and their ability to withstand space environmental conditions.

Through this study, two polymers printed via Fused Filament Fabrication (FFF) are compared: PolyEtherKetoneKetone (PEKK) and PolyEtherEtherKetone (PEEK). These high-temperature materials are used for aerospace applications as composite matrixes [5]. 3D printed PEEK has been considered in the making of a nanosat structure [6] and even a compliant gripper for lunar equipment [7]. This work aims at determining which of these two materials are most adapted for the development of a compliant mechanism. First, 3D printed PEKK and PEEK are characterized by performing tensile, flexural and Differential Scanning Calorimetry (DSC). Then, the mechanical properties of the best-performing material are used to create a finite element analysis of a section of the joint, the cross-axis pivot. Then, the model is validated with experimental measurements using image correlation.

2) Materials and Methods

2.1) Material

The materials used for this study are KIMYA PEKK-A filament by Arkema and Z-PEEK filament supplied by Zortrax. Their properties are described Table 1.

Table 1: Filament properties according to their supplier

	PEKK-A	Z-PEEK
Density [g/cm^3]	1.29	1.3
Diameter [mm]	1.75	1.75
Glass transition temperature [°C]	159	143
Melting temperature [°C]	308	343

2.2) Printing of specimens

The CAD of the different specimens were modelled on CATIA V5 then transferred to the slicing software Cura. Before printing, the filaments were dried in an oven at 120 °C for 4h, then kept in a temperature-controlled environment at 55 °C until the specimens are printed. Ther printer used is a

VOLUMIC SC2 Ultra and the printing parameters used are presented in Table 2. Only the nozzle temperature differs from a filament to another: 365 °C for Z-PEEK and 345 °C for PEKK-A to accommodate with melting temperatures.

Table 2: General printing parameters

Layer thickness [mm]	0.2	Printing speed [mm/s]	25
Flow compensation [%]	5	Support height [mm]	0.8
Support type	triangular	Support density [%]	70
Bed material	Ultem sticker	Bed temperature [°C]	140

Tensile and bending specimens are printed in batches of 5. Their dimensions respect the ISO 527-2 and ISO 178 test standards respectively. Their inner structure induced by 3D printing is described in Table 3.

Table 3: Structural printing parameters of tensile and bending specimens

Numbers of top/bottom layers	0
Number of walls	0
Infill type	Zigzag
Infill rate [%]	100
Printing direction [°]	0

The cross-axis pivot with its more complex geometry is displayed in Figure 1. Contrary to the design that is mostly known in literature [8], its blades have variable thickness and widths throughout their lengths to improve their flexibility and the compactness of the whole joint. The structural printing parameters of the pivot are shown in Table 4.

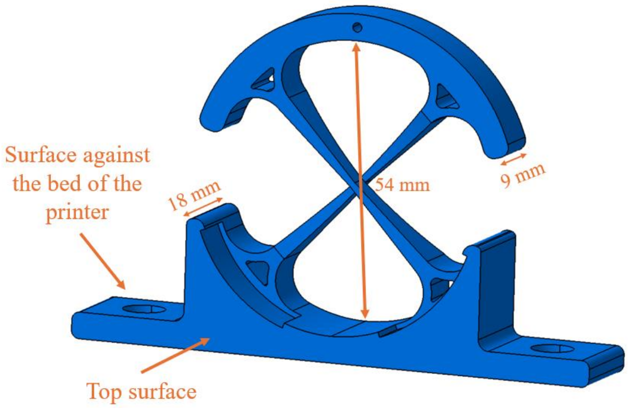

Figure 1: Dimensions of the cross-axis pivot

Table 4: Structural printing parameters of the cross-axis pivots

Numbers of top/bottom layers	5
Number of walls	4
Infill type	Grid
Infill rate [%]	70
Printing direction [°]	0

As recommended by the suppliers and literature [9], [10], the specimens were annealed after printing to increase their crystallinity and mechanical properties. They were put in a metal container filled with sand to prevent shrinkage and to ensure the uniformity of the temperature fluctuations. In Figure 2, their annealing program is described. Those printed with the PEKK-A filament spent 3h at 100 °C then 4h at 200 °C while Z-PEEK specimens were annealed for 3h at 100 °C and 5h at 250 °C. After, they were left in the oven until they reached room temperature.

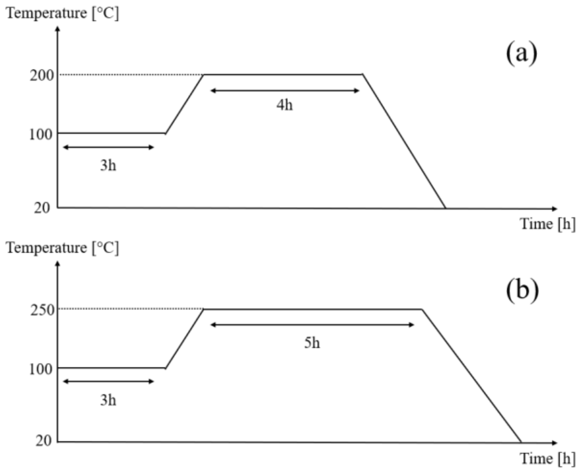

Figure 2: Annealing program of the specimens printed with the PEKK-A filament (a) and the Z-PEEK filament (b)

2.3) Equipment

DSC tests were performed on a TA INSTRUMENTS Q100 on 5 to 10 mg samples. For these tests, three specimens of each material were analyzed under nitrogen at 50 ml/min. The analysis is maintained at 50 °C for 2 min then the temperature is raised to 400 °C at 10 °C/min. Then follows an isothermal of 2 min before cooling the sample to 50 °C at 10 °C/min. The results of these tests were processed on the software TA Universal Analysis. The crystallinity rate χ of the specimens are calculated with the equation (1), with ΔH_m the melting enthalpy of the specimen and ΔH_m^0 the melting enthalpy of a 100 % crystalline PEEK. According to literature [11], the value of ΔH_m^0 of PEEK is 130 J/g and can be used to calculate the crystallinity rate of PEKK due to the similarity of their structure.

$$\chi = \frac{\Delta H_m}{\Delta H_m^0} * 100\ \% \quad (1)$$

Both tensile and bending tests were performed on an INSTRON 5982 tensile machine with a 100 KN sensor. Tensile tests were done at 1 mm/min according to the ISO 527 test standard [12]. The elongation is measured with an AVE 2 extensometer. The three-point-bending tests are carried out according to the ISO 178 test standard [13] at 2 mm/min. The data from these tests were computed using Bluehill Universal 3 software.

The experiments of the cross-axis pivot were analyzed using GOM CORRELATE 2018, an image correlation software. The results of these tests were compared to a finite element analysis performed on ABAQUS V6-14.

3) Results

3.1) Material characterization

Results of the tensile, flexural and DSC are presented in Table 5. PEKK-A and Z-PEEK specimens have similar elasticity and flexural modulus around 3200-3300 MPa which correlates with literature [14], [15]. However, PEKK-A has a tensile strength and a 0.2 % offset yield strength that is 22 % and 27 % higher than Z-PEEK. Though PEKK-A specimens had a brittle fracture, Z-PEEK specimens had necking and a larger strain at tensile strength by 17 %. The ultimate flexural stress and the stress at conventional deflection are also 14 % and 8 % higher.

In terms of thermal properties, both materials have their glass transition temperature increased from the annealing, and PEEK has the highest at 168 °C against 158 °C. The crystallinity rate of PEKK-A is lower than Z-PEEK by 7 %. This phenomenon is well-documented in literature [16]. PEKK-A has a lower melting temperature, which makes its printing easier.

Both materials have shown satisfactory results in terms of mechanical and thermal properties. However, PEKK-A is selected for experiments and model correlations for its higher Yield Strength and its ease of printing.

Table 5 : Mechanical and thermal properties of PEKK-A and Z-PEEK specimens

	PEKK-A	Z-PEEK	Difference
Tensile properties			
Elasticity Modulus [MPa]	3204 ± 289	3306 ± 369	**3 %**
Tensile Strength [MPa]	103 ± 2	91 ± 2	**22 %**
Strain at Tensile Strength [MPa]	4.6 ± 0.1	5.6 ± 0.0	**17 %**
0.2 % offset Yield Strength [MPa]	79 ± 12	58 ± 10	**27 %**
Flexural properties			
Flexural Modulus [MPa]	3140 ± 221	3276 ± 122	**4 %**
Ultimate Flexural Stress [MPa]	170 ± 5	149 ± 1	**14 %**
Stress at Conventional Deflection (3.5 %) [MPa]	117 ± 5	108 ± 5	**8 %**
Thermal properties			
Glass Transition Temperature [°C]	158 ± 1	168 ± 0.4	**6 %**
Melting Temperature [°C]	303 ± 0.3	341 ± 1	**11 %**
Cristallinity Rate [%]	16 ± 1	23 ± 3	**7 %**

3.2) Model and Experiments correlation

Once printed and annealed, a PEKK-A cross-axis pivot is tested according to the set-up displayed in Figure 3. One extremity of the part is embedded while various weights (30 g, 80 g, 130 g, 180 g) are hanged from the other. Pictures of the mechanism are taken each time a weight is added. Then the experiment is repeated five times. The mean displacements of the five points in Figure 3 are measured with the image correlation software GOM CORRELATE 2018.

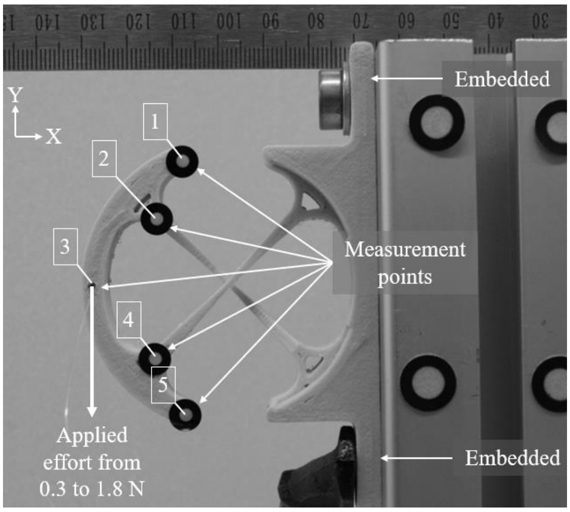

Figure 3: Set-up of the cross-axis pivot experiments

A static general finite element analysis of the experiment is carried out using the results from the last mechanical characterization of 3D printed PEKK-A. The material is assumed to be homogenous and isotropic with a elasticity modulus of 3304 MPa and a Poisson's ratio of 0.4 [17]. The pivot is meshed with volumic quadratic C3D10 elements. Their length goes from 0.5 mm on the blades to 2 mm on the rest of the part. A total of 143947 tetrahedral elements and 222097 nodes are used. The same boundary conditions as the experiment are applied to the model and displayed Figure 4. A reference point is created at the centre of the drilling site at Point 3 and linked to its surface using a tie interaction. A concentrated force of -1.8 N, corresponding to the maximum weight hanged to the pivot, is applied to the reference point towards the Y axis. The other drillings are constrained in every degree of freedom.

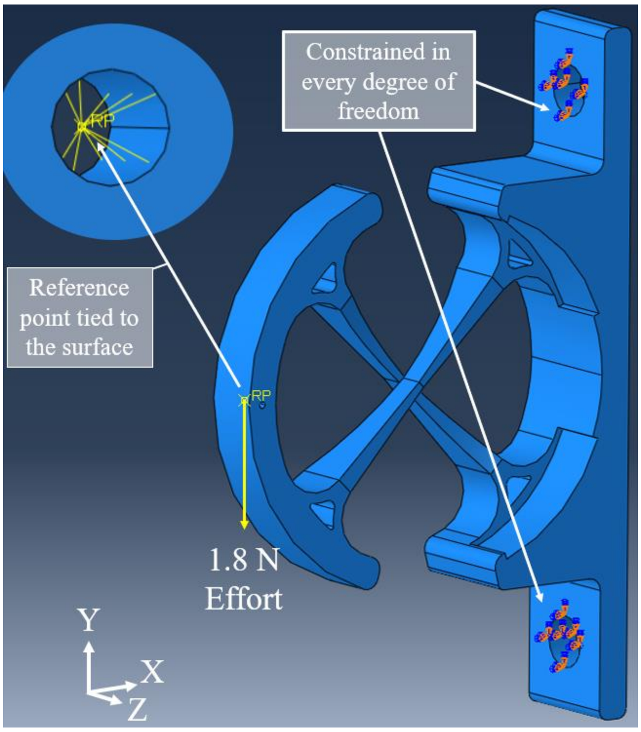

Figure 4: Boundary conditions of the finite element analysis of the cross-axis pivot

Figure 5 displays the displacement on the X axis and the distribution of stress along the part according to the Von Mises criteria. The displacement of each node presented in Figure 5 in both the X and Y axis are collected and compared to the experiments in Figure 6.

The maximum stress applied to the cross-axis pivot is 29.7 MPa, which is lower than the previously defined yield stress of PEKK-A. This indicates that under these boundary conditions, the material still behaves elastically, which is confirmed by the linearity of the cross-axis pivot's response in the experiments. On the X axis, the behavior of the five points is close to the tests. At 1.8 N, between the model and the experiments, the difference of displacement of the five points only varies from 3 % to 9 %. However, on the Y axis, the modeled cross-axis pivot seems stiffer than the printed one. Indeed, even if points 2, 3 and 4 have a correlation between 6 and 10 %, points 1 and 5 have a 24 % correlation between the model and the tests. Previous work [1] showed by X-ray tomography the presence of various porosities caused by the FFF process that could explain these differences.

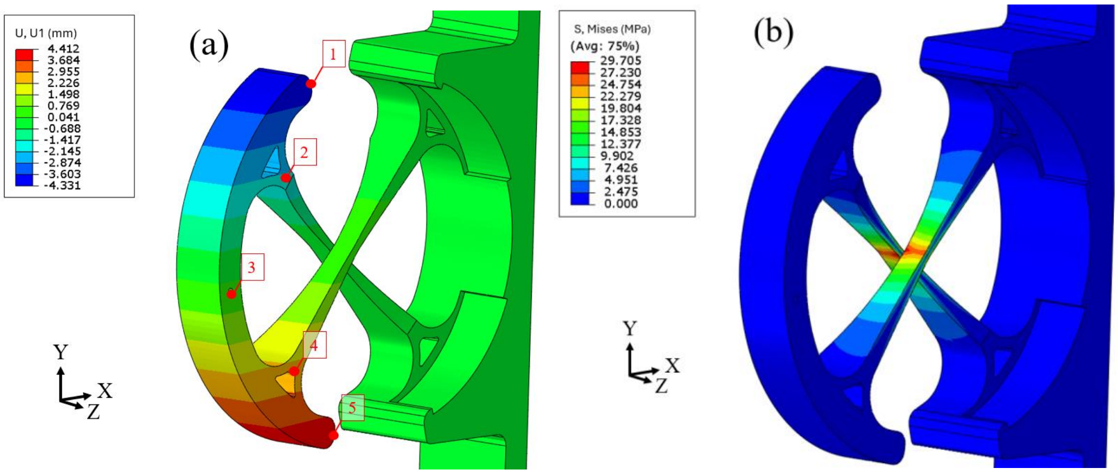

Figure 5: Results of the finite element analysis: (a) displacement along the X axis, (b) distribution of stress along the part according to the Von Mises Criteria

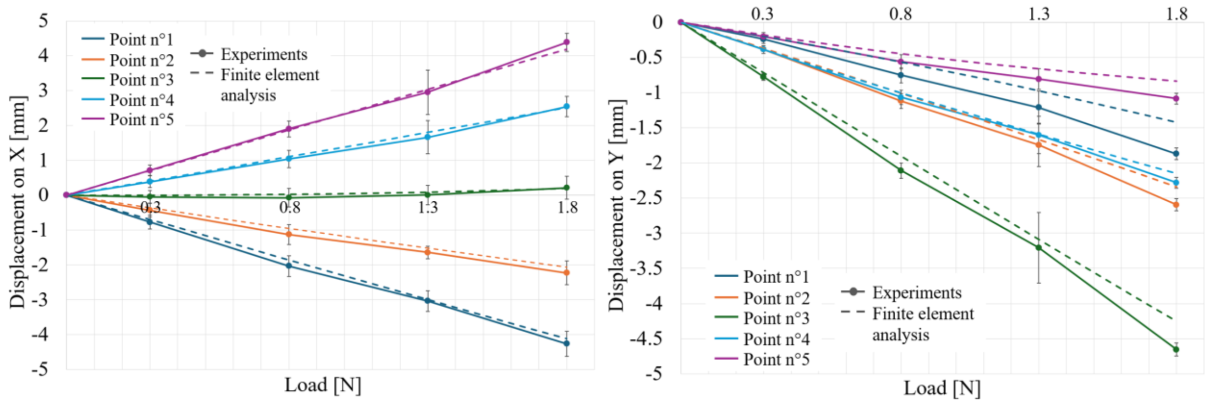

Figure 6: Displacement on the X and Y axis of the five studied points depending on applied load: comparison between the experiments and the finite element analysis

4) Conclusion and outlook

This study aimed at characterizing two high-temperature thermoplastics, PEKK-A and Z-PEEK. They showed similar elasticity and flexural modules. However, PEKK-A has a higher mechanical yield strength and is easier to print, which is why, despite having a higher glass transition temperature, Z-PEEK was not selected for the rest of the study.

A cross-axis pivot was printed in PEKK-A and subjected to mechanical stress that was analyzed with image correlation software. Its mechanical behavior was then compared to a finite element model using the tensile properties previously acquired. With less than 10% test/model error, 3D printed PEKK-A can be assumed to be homogenous and isotropic when studied within its elastic deformation phase. However, considering the porosity created by 3D printing might improve the accuracy of the model.

Using the previous results and model, future work will focus on studying the damping behavior of 3D printed PEKK-A as well as the vibration response of the cross-axis pivot.

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