Performance Preservation and Hydrolytic Degradation Analysis of Parylene-C Coated 3D-Printed PLA Under Simulated Physiological Conditions

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ABSTRACT
Total hip arthroplasty (THA) is a widely employed procedure to restore the function of an impaired joint; however, despite their widespread use, the longevity and durable performance of polymeric acetabular liners remain a primary challenge due to wear and hydrolytic degradation. Polylactic acid (PLA) is a promising material for patient-specific implants due to its biocompatibility and good printability, but moisture-induced degradation limits its use in permanent load-bearing parts. This article describes a finite element study to evaluate the use of Parylene-C coating to improve both the long-term mechanical and tribological performance of 3D-printed PLA acetabular liners. First, tensile, compression and pin-on-disc wear of uncoated PLA were built in ABAQUS and validated with published experimental data with a very good agreement: less than 2.2% deviation for compressive strength, 4.7% for coefficient of friction (COF) and 8% for wear rate from the average values respectively. The hydrolytic degradation was then simulated using a transient mass diffusion model with the assistance of an USDFLD subroutine for representing moisture dependent material degradation through SBF immersion over a 12-week period. To find the best protective layer, Parylene-C coatings with thicknesses of 5, 15, and 30 µm were investigated. Coating of PLA filaments with a 30 µm layer provided the greatest moisture diffusion resistance, preserving 98.5% elastic modulus after moist environment exposure for 12 weeks (with respect to uncoated PLA: recovery of only 78.7%). The optimized coating was then applied on validated tensile, compression and tribological models which showed improvements of 2-3% in tensile and compressive strengths, 6–7% reduction in the coefficient of friction, wear rate reduction by up to 22-27% relative to uncoated PLA. These results show a 30 µm Parylene-C coating protects against hydrolytic degradation and yields high long-term mechanical and tribological stability of fabricated PLA, supporting its use as a protective implant for additively manufactured acetabular liners in total hip arthroplasty.
Keywords: 3D-Printed Polylactic Acid (PLA); Parylene-C Coating; Hydrolytic Degradation; Finite Element Analysis; Mechanical and Tribological Properties; Simulated Body Fluid (SBF); Acetabular Liner
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1. Introduction

Total hip arthroplasty (THA) is one of the most successful orthopedic procedures conducted for the treatment of end-stage joint diseases, with the acetabular liner playing a crucial role in the articulation of the hip and load transmission. Conventional 3D printing techniques have been used to produce acetabular liners from ultra-high-molecular-weight polyethylene (UHMWPE) which has been found to be an ideal material for these applications due to its high wear resistance and biocompatibility; its main drawback is high processing costs and poor suitability for conventional 3D printing, this has motivated the exploration of alternative materials [1,2]. With the advent of Additive Manufacturing (AM), specifically Fused Deposition Modeling (FDM), patient-specific orthopedic implants can be manufactured, and the use of polylactic acid (PLA) is considered to be an attractive material due to its printability, biocompatibility and design flexibility [3,4]. However, the hydrolytic degradation of PLA in physiological conditions restricts its use in load-bearing implants, and thus the mechanical and tribological properties of PLA. To overcome this limitation, the protective surface modification has been called. The method of Parylene C, which is deposited in a thin film layer of moisture barrier properties and uniform/pinhole-free deposition by means of Chemical Vapor Deposition (CVD), is one of the approaches that is a promising biocompatible coating. Yet, this application as a protective coating for PLA acetababular liners has not been well researched [6]. In this research, the biodegradability of 3D-printed PLA acetabular liners is decreased using a coating made by Chemical Vapor Deposition (CVD) of Parylene C. A full finite element model has been created in ABAQUS to test the effectiveness of this approach. In the first step, the study consists of the validation of the numerical model by simulation of the tensile, compressive behaviour and tribological behaviour of uncoated PLA with the experimental data extracted from the literature. Hydrolytic degradation of PLA is then simulated in Simulated Body Fluid (SBF) for 12 weeks, and the performance of the three coating thicknesses, (5, 15 and 30 μm) is evaluated to determine which coating thickness is most effective. Lastly, the validated models are coated with optimized 30 μm Parylene C, and the changes in mechanical and tribological properties after 12 weeks of exposure in SBF are compared with those of uncoated PLA.

2. Materials and Methods

A finite element analysis (FEA) approach was used in this study to analyze the mechanical, tribological, and degradation behaviour of 3D-printed PLA acetabular liners coated with Parylene C and uncoated. The methodology was divided into three parts, namely: (i) validation of uncoated PLA models, (ii) degradation modelling and optimization of coating, and (iii) assessment of coated specimens under physiological conditions.

2.1 Material Properties

Polylactic acid (PLA), a biodegradable thermoplastic polymer with excellent printability, biocompatibility and easy fabrication, was chosen as a substrate material in this study. The material was simulated as a isotropic elastic–plastic material using ABAQUS. A set of mechanical properties were adopted from published experimental studies on 3D printed PLA using FDM and used throughout the finite element simulations: Young's modulus (3.3 GPa), Poisson's ratio (0.35), density (1.25 g/cm³), and yield strength (60 MPa). The protective coating was chosen as parylene C due to its excellent biocompatibility, chemical inertness and superior moisture barrier properties [7]. In the finite element model, the coating was assumed to be homogeneous, isotropic and linearly elastic. The Young's modulus, 2.76 GPa, the Poisson's ratio, 0.40 and the density, 1.289 g/cm³, were assumed according to literature and manufacturer information [7, 8, 9]. The coating thickness was modeled as being 5µm, 15 µm and 30 µm, and perfect adhesion of the interface between PLA and Parylene C was assumed by applying tie constraints in ABAQUS. Parylene C's excellent conformality and barrier properties are appropriate for protecting moisture-sensitive biodegradable polymeric implants [10]

2.2 Phase 1: Validation of Uncoated PLA

The computational model was validated by simulating tensile tests (ASTM D638), compression tests (ASTM D695) and pin-on-disc wear tests. Tensile and compression simulations were performed and the stress–strain responses compared with the experimental responses. A tribological analysis was carried out by testing a PLA pin under a constant load of 20 N, and the wear volume was calculated according to the Archard's wear equation: V=k (F□s)/H The wear volume V is proportional to the wear coefficient k, load F, sliding distance s and hardness H of the material [11].

2.3 Phase 2: Degradation Modelling and Coating Optimization

Degradation modelling and coating optimization aims at developing models of degradation phenomena and optimizing the coating structure. Continuum damage model was used to simulate the hydrolytic degradation of PLA in the Simulated Body Fluid (SBF, pH 7.4, 37°C) for 12 weeks. The damage coefficient (D) was used to model material degradation by reducing the elastic modulus of the material as $d=(1-D)\ E$, [12]. Then, the materials were coated with Parylene C films of 5, 15, and 30 µm thickness using tie constraints, and the effectiveness of the coatings to inhibit degradation was assessed. The coating with 30 µm gave the best protective performance due to the damage coefficient. The performance evaluation of coated specimens is the subject of this phase.

2.4 Phase 3: Performance evaluation of coated specimens

The three validated tensile, compression and wear models were coated using the optimized Parylene C coating of 30 µm. The mechanical properties and wear performance of the simulated SBF samples were then compared with the uncoated PLA models to determine the ability of the coating to maintain their structural integrity and tribological performance.

The computational procedure was carried out with ABAQUS Finite Element Analysis (FEA) to systematically evaluate and optimize a 3D-printed PLA acetabular liner coated with Parylene C [13]. First, uncoated PLA FEA models were validated with published experimental results for tensile, compressive and tribological properties under a constant load of 20N [14, 15]. Next, a continuum damage mechanics (CDM) approach was used to simulate the hydrolytic degradation of PLA in a Simulated Body Fluid (SBF) over 12 weeks of degradation with the increase in damage coefficient [16] representing the progressive degradation of the material stiffness. The degradation model was then used to assess the effectiveness of simulated Chemical Vapor Deposition (CVD) Parylene C coatings having thicknesses of 5, 15 and 30 µm, with the excellent conformal deposition and moisture barrier properties of Parylene C [17]. The

30 μm thickness, determined as the lowest progressive damage coefficient, was applied to the validated tensile, compression and wear models to determine the retention of mechanical and tribological properties after 12 weeks in SBF.

3. Mechanical and tribological properties of uncoated PLA Validation.

The mechanical and tribological behaviour of 3D-printed PLA was compared with published experimental results for the validation of the finite element model. Tensile, compression and pin on disc wear simulation processes were carried out in ABAQUS based on the material properties and testing conditions mentioned in the literature. The simulated stress–strain response, coefficient of friction and wear rate results were found to be in good agreement with the experimental results, thus proving the accuracy of the developed computational model.

3.1. Validation of Experimental Tensile Test using Abaqus

According to Brischetto and Torre (2020), the mechanical response of a standard dog-bone sample produced by Fused Deposition Modeling (FDM) technique using Polylactic Acid (PLA) was simulated numerically to validate the finite element framework. The specimen geometry was designed based on the ASTM D638 specimen in Figure 1, have a length of 180 mm, a gauge length of 57 mm, a gauge width of 13 mm, a thickness of 5 mm, and a fillet radius of 76 mm. The manufacturing parameters included 100% infill density, a first-layer thickness of 0.2 mm printed at 215°C, and the following layers of 0.1 mm at 210°C, were used in a finite element simulation in ABAQUS, which were based on the experimental study. The Young's modulus of the PLA material was taken as 2550 MPa, which is the same as the reported experimental value [18], and the density of the PLA materials was taken as 1.24 g/cm³ (1240 kg/m³). The experimental crosshead speed was 5 mm/min and was reproduced for the experimental tensile test condition by applying a tensile load of 4010 N to the
specimen.

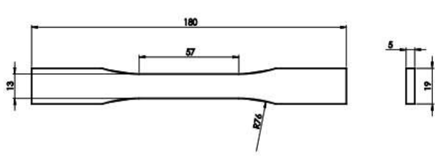

Figure 3.1: Tensile test specimen as per ASTM D638

3.2 Validation of Experimental Compressive Test using Abaqus

The mechanical properties of a typical compression test piece made from Fused Deposition Modeling (FDM) Polylactic Acid (PLA) were modeled and simulated to validate the computational framework under compressive loading. The specimen geometry was designed, following ASTM D695 standard for compression testing, to be 40 mm × 12.7 mm × 12.7 mm with square cross-section. The 100% infill density and ±45° raster angle were used as physical manufacturing conditions with a printing nozzle temperature of 215°C for the first layer and 210°C for the subsequent layers. A Static General analysis step was used for the finite element analysis (FEA) in Abaqus. The PLA was given an initial Young's Modulus of 2550 MPa, a Poisson's ratio of 0.35, and a density of 1.24 g/cm³ (1240 kg/m³) [18]. In order to simulate the quasi-static, uniaxial compression test, the top surface of the specimen was subjected to a uniformly distributed compressive load of 8800 N while the bottom surface was completely immobilized.

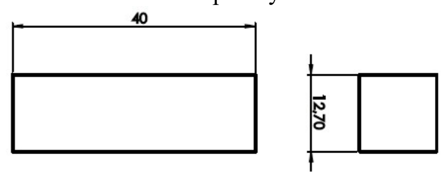

Figure 3.2: Compressive test specimen as per ASTM D695

3.3 Validation of Experimental Wear Test using Abaqus

A three-dimensional pin-on-disc wear model was designed in Abaqus/CAE 2025 to simulate the dry sliding of a Pin made from Polylactic Acid (PLA) and a Disc made from steel under tribological loading conditions, in order to validate the computational framework under the tribological loading conditions [19, 20]. The configuration of the computational model was a cylindrical PLA pin with a diameter of 9.59 mm and a length of 47.8 mm and a steel disc with a diameter of 100 mm and a thickness of 10 mm, as seen in figure 3, and used in experimental studies previously conducted for tribological properties of FDM-printed PLA [21] and [22].

The PLA specimen was assumed to be manufactured using Fused Deposition Modeling (FDM) with a 100% infill and a raster orientation of ±45 degrees, a nozzle temperature of 215ºC for the first layer and 210ºC for subsequent layers similar to those reported in the literature to optimize the mechanical and tribological properties of PLA [22, 23], and a layer height of 0.2 mm and 0.1 mm for the first and subsequent layers, respectively. A Static General analysis step was used for the finite element analysis (FEA), using surface-to-surface contact interaction [19]. The Young's Modulus, Poisson's ratio and density of PLA material were taken as 2550 MPa, 0.35 and 1.24 g/cm³ (1240 kg/m³), respectively, according to the values reported for the material printed by FDM and the steel disc was considered rigid

relative to the polymer pin [21]. The reference point was subjected to a normal load of 20 N with the top surface of the pin, and the bottom surface of the steel disc was completely fixed (U1 = U2 = U3 = 0 and UR1 = UR2 = UR3 = 0).
The steel disc was rotated at 120, 150, 180, and 210 rpm (sliding velocity of 0.46, 0.58, 0.70, and 0.81 m/s, respectively) about the Z-axis to achieve sliding motion, with test conditions following those with the pin-on-disc test reported in the literature [21] and [24]. The simulation time was 1200 s in both loading condition. The finite element model was set up to generate von Mises stress, contact pressure (CPRESS), frictional shear stress (CSHEAR1), wear depth (CWEAR), coefficient of friction (μ) and wear rate in order to assess the tribological behavior of the PLA material under different sliding velocities [19, 20]. These parameters were then compared to the literature's available experimental data to validate the numerical prediction [21, 22].

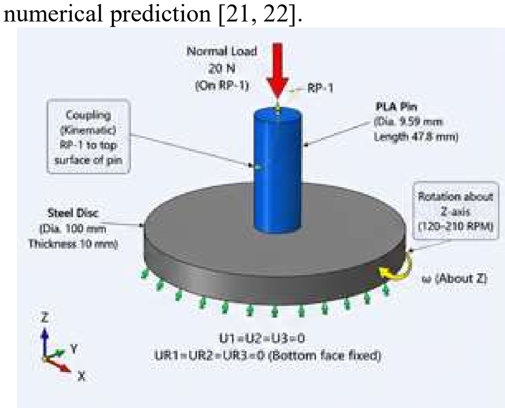

Figure 3.3: Pin on disc test specimen [24]

4. Degradation Modelling and Coating Optimization

PLA samples were immersed in Simulated Body Fluid (SBF) at 37°C for 12 weeks to investigate the hydrolytic degradation of both uncoated and Parylene-C coated specimens [25, 26]. A continuum damage model was employed to evaluate the progressive reduction in elastic modulus caused by moisture absorption [27]. The uncoated PLA exhibited continuous degradation, whereas the Parylene-C coated specimens showed significantly lower damage due to the excellent moisture barrier properties of the coating [28, 29]. Coating thicknesses of 5, 15, and 30 μm were investigated, with thicker coatings providing greater resistance to hydrolytic degradation [30].

4.1 Hydrolytic Degradation of Uncoated PLA in Simulated Body Fluid (SBF)

A three-dimensional finite element diffusion model was created in Abaqus/CAE 2025 with a simplified FDM-printed PLA specimen (50 ×10 ×3 mm). The material characteristics of PLA were adopted from previous experiments [31,32] young's modulus = 3300 MPa, Poisson's ratio = 0.35 and density = 1.24 g/cm3 Mass Diffusion analysis was conducted assuming the diffusion coefficient of water in PLA under physiological condition is 1×10^{-12} m²/s [25, 27]. The specimen was immersed in SBF at 37°C for 12 weeks with an initial moisture concentration of zero and a normalized surface concentration of one. Hydrolytic degradation was incorporated via a subroutine for USDFLD with first order damage evolution, using the hydrolysis constant (0.02 week⁻¹) applied in the degradation model proposed by Vieira and co-workers [27].

$$\partial C/\partial t = D\nabla^2 C$$

$$dd/dt = k\,C\,(1 - d)$$

$$E = (1 - d)\,E_0$$

where C is the normalized moisture concentration, D is the diffusion coefficient, k is the hydrolysis rate constant, d is the damage variable, and E_0 and E represent the initial and degraded Young's modulus, respectively [27].

4.2 Hydrolytic Degradation of Parylene-C coated PLA with in Simulated Body Fluid (SBF)

A finite element diffusion-coupled model was established to examine the hydrolytic degradation behavior of PLA coated with Parylene-C. Flat PLA samples (50 × 10 × 3 mm) were then coated with Parylene-C thicknesses (5, 15, and 30 μm) by the CVD process [28,29]. The Young's modulus of the PLA substrate was set to 3300 MPa, Poisson's ratio was 0.35, density (g/cm³) = 1.24 [7,8], and a diffusion coefficient of 1×10^{-12} m²/s was assigned to it as well for this simulation [7]. The parameters of Young's modulus (2760 MPa), Poisson's ratio (0.40), density (1.289 g/cm³), and moisture diffusion coefficient (1×10^{-15} m²/s) were adopted for the Parylene-C coating according to its good barrier property against moisture [28, 29, 30].
The Mass Diffusion analysis step simulated moisture diffusion in SBF (37Â°C) for a period of 12 weeks. Hydrolytic degradation was only applied to the PLA substrate via a USDFLD subroutine as Parylene-C was assumed to be purely acting as a passive moisture barrier [27, 28, 29].

5. Performance Evaluation of Coated PLA Specimens

The optimized 30 μm Parylene-C coating identified during the coating optimization stage was applied to the validated PLA models to evaluate its effectiveness under simulated physiological conditions. The coated tensile, compression, and tribological specimens were analyzed after 12 weeks of SBF immersion to assess the retention of mechanical and wear performance compared with uncoated PLA.

5.1 Tensile Behaviour of Parylene-C Coated PLA after SBF Immersion

Parylene-C (30 µm) layer at the surface of a tensile specimen of polylactic acid (PLA) (ASTM D638 Type V): A three-dimensional finite element model in Abaqus/CAE 2025 Academic edition. The PLA substrate was modeled from the FDM process assuming that the Parylene-C coating is deposited using Chemical Vapor Deposition (CVD) [28, 29]. The coated specimen was subjected to Mass Diffusion analysis, placing the immersed sample in SBF at 37 °C for 12 weeks, with diffusion coefficients of 1×10^{-2} m²/s [27], and of PLA and Parylene-C ([28], [29]). Hydrolytic degradation in the PLA substrate was carried out by a USDFLD subroutine [27]. The Static General tensile analysis with ASTM D638 load conditions, based on the degraded material properties, was then performed.

5.2 Compressive Behaviour of Parylene-C Coated PLA after SBF Immersion

A three-dimensional finite element model of a 30 µm Parylene-C coated PLA compression specimen (ASTM D695) was developed using the same degradation methodology [27, 28]. The coated specimen was immersed in SBF at 37°C for 12 weeks, and hydrolytic degradation was incorporated only in the PLA substrate using a USDFLD subroutine. The degraded material properties were then employed in a Static General compression analysis according to ASTM D695 [15].

5.3 Tribological Behaviour of 30 µm Parylene-C Coated PLA after 12 Weeks of Simulated Body Fluid (SBF) Immersion

A three-dimensional pin-on-disc finite element model was used to study the tribological behaviour of 30 µm Parylene-C coated PLA. The properties of the material that has been degraded were used in a SFFF wear simulation based on the Archard wear model [31] after performing a diffusion analysis in SBF at 37°C for 12 weeks. The constant normal load of 20 N was held as the steel disc rotated at 120, 150, 180 and 210 rpm (0.46–0.81 m/s). Here, the model predicted for friction coefficient (µ), wear rate (w_r), contact pressure (σN); von Mises stress and frictional shear stress and wear depth were also compared against uncoated PLA to study the impact of these 30 µm thick Parylene-C coatings [31,32].

6. Result and Discussion

This section presents and discusses the numerical results obtained from the validated finite element models for the mechanical, tribological, and degradation performance of PLA specimens.

6.1 Tensile Test Validation of FDM-Printed PLA

Validation of the tensile behaviour of FDM-printed PLA specimen in comparison to Brischetto et al. (2020). The simulation engineering stress–strain curve was in a good agreement with the experimental results over the elastic and plastic region. A maximum von Mises stress predicted for the ABAQUS model was 61.83 MPa, and the experimental ultimate tensile strength resulted in average values of 61.7 MPa. As expected, the maximum stress concentration was located in the gauge section where failure occurred aerobically in experimentally determined locations. The tensile specimen ultimate stress and strain see with simulated stress-strain curve generated using ABAQUS is shown in Fig. 6.1

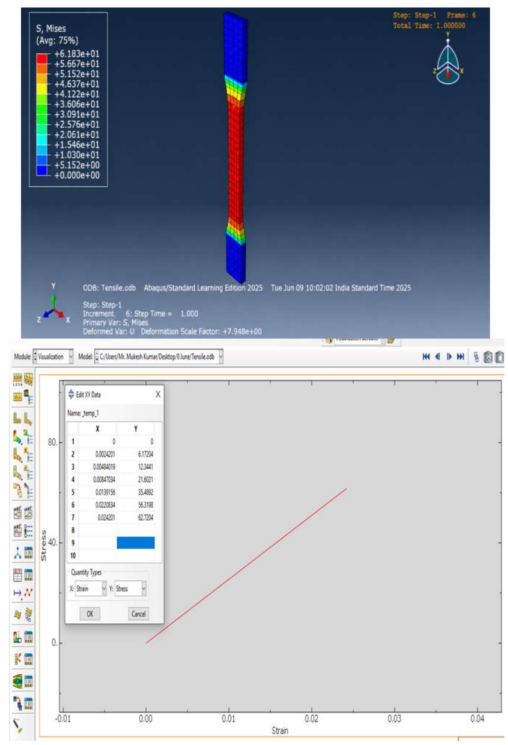

Figure 6.1: Tensile test specimen under loading condition in ABAQUS & stress –strain curve generated by ABAQUS

The minor differences in strain response were associated with the finite element model presuming that all material was isotropic, while FDM-printed PLA is anisotropic owing to raster orientation, interlayer bonding and manufacturing defects. In summary, the very close match between both experimental and numerically determined material properties confirmed their full potential for a future degradation, mechanical and tribologic analysis of PLA acetabular liners employed in a physiological condition. Experimental characteristics vs. numerically predicted stress–strain values are given in Table 1 and illustrate the results of simulations (Figure 6.2).

Table 1. Comparison of Experimental and Abaqus Tensile Results

Experimental (Brischetto et al., 2020)		Abaqus Simulation	
Strain	**Stress (MPa)**	**Strain**	**Stress (MPa)**
0	0	0	0
0.005	12.8	0.00242	6.17204
0.01	25.5	0.00484	12.3441
0.015	38.3	0.00847	21.6021
0.02	49.5	0.013916	35.4892
0.026	58.5	0.022083	56.3198
0.032	61.7	0.024201	62.8204

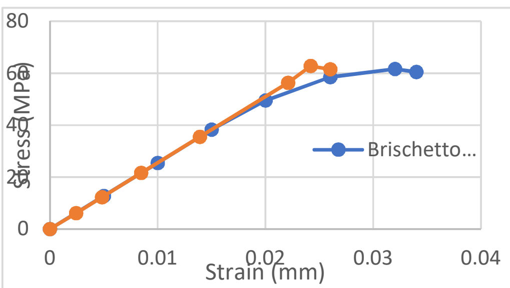

Figure 6.2: Stress- Strain curve Comparison of Experimental data and Simulation data

6.2 Compression Behaviour of PLA

The compressive behaviour of the 3D-printed PLA specimen was assessed by means of finite element analysis (FEA) in Abaqus and compared to experimental results cited from the work performed by Brischetto et al. (2020). The numerical model was validated against the experimental stress–strain response. The comparison shown is for the elastic loading region and illustrates a good agreement between the simulation with data from published experiments.

The ultimate stress and strain values of the tensile specimen are shown in Figure and compared between experimental and simulated stress–strain values in Table 2 and Figure 6.3.

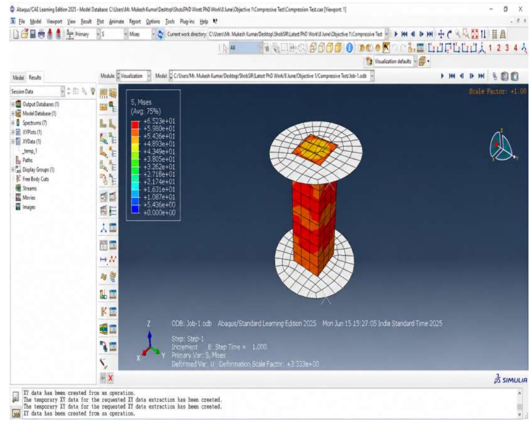

Figure 6.3: Compressive test specimen under loading condition in ABAQUS

Table 2. Comparison of Experimental and ABAQUS Compression test Results

Brischetto et. Al. (2020)		Abacus	
Strain (mm)	**Stress (Mpa)**	**Strain (mm)**	**Stress (Mpa)**
0	0	0	0
0.005	10.2	0.00291355	5.92872
0.01	20.4	0.00583951	11.8821
0.015	30.5	0.0102448	20.8449
0.02	40.7	0.016872	34.3258
0.025	50.9	0.0268108	54.5454
0.03	61.1	0.0293857	59.7849

The experimental stress showed almost a linear increase to 61.1 MPa (at a strain of 0.03), with the Abaqus model above predicting a maximum compressive stress value of only 2.2% less (59.78 MPa at strain = 0.0294). The good agreement between the experimental and numerical stress–strain curves verifies that the material properties, boundary conditions, and loading configuration adopted are correct. Small discrepancies are explained by the isotropic material assumption, as well as not accounting for FDM related defects—interlayer porosity and bonding flaws. In general, the validated Abaqus model accurately predicts the compression behaviour of FDM-printed PLA and is usable for follow-up FEA on Parylene-C coated specimens and later acetabular liner applications.

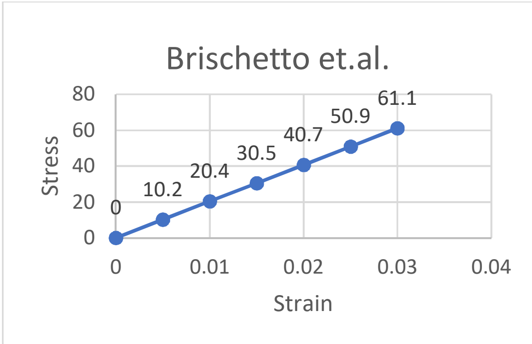

Figure 6.4: Stress-Strain curve from experimental results of Brischetto et. al (2020)

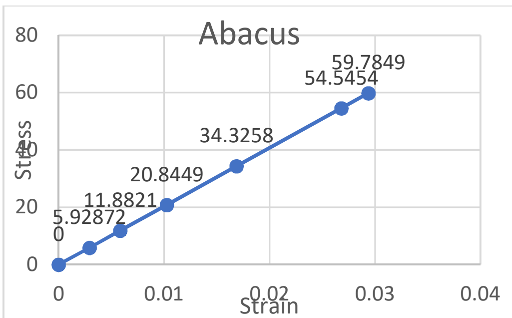

Figure 6.5: Stress-Strain curve from ABAQUS results

6.3 Tribological Validation of Pure PLA Using Abaqus Pin-on-Disc Simulation

Cross-sectional wear tests (up to 8 m sliding distance) of a pin-on-disc finite element model software were implemented in this work on the tribological behaviour of 3D-printed PLA, developed in Abaqus/CAE 2025 and validated against published experimental results. Nonlinear static and dynamic simulations were implemented under applied constant normal load of 20 N sliding speeds in the range of 0.46–0.81 m/s, with maximum von Mises stress (62 MPa), contact pressure (89 MPa) located at pin–disc contact interface, while maximum friction shear stress was around 40 MPa meaning that mechanical loading would mainly locate within the contact region.

Simulation predicted the maximum wear depth around 0.12 mm, with real material loss concentration on sliding plane, which matched well with actual abrasive and adhesive wore phenomena of PLA. Additionally, the trends of the simulated coefficient of friction and wear rate were consistent with the experimental ones, with deviations ranging only from 4.5 to 4.7%. The good agreement calculations on the numerical results and experiment ones validates our developed Abaqus based tribological model.

The results of experimental and simulation data for Coefficient of Friction and wear rate are shown in table 3.

Table 3. Comparison of Coefficient of friction and wear rate Experimental and ABAQUS

Parameter	Speed (m/s)	Palaniandy L. et. al. (2023)	Abaqus	Difference (%)
Coefficient of Friction (μ)	0.46	0.6702	0.64	4.48%
	0.58	0.5770	0.55	4.68%
	0.70	0.5243	0.50	4.63%
	0.81	0.5970	0.57	4.52%
Wear Rate (mg/m)	0.46	0.00102	0.00108	5.88%
	0.58	0.0028	0.00265	5.36%
	0.70	0.00358	0.00335	6.42%
	0.81	0.0011	0.00118	7.27%

In general, the tribology behaviour of 3D-printed PLA under dry sliding conditions was accurately reproduced by finite element simulation. The predicted stress distributions, contact pressure, friction behaviour and wear characteristics were in fair agreement with experimental results. The minor differences are due to the simplified numerical model, which does not represent thermal softening behaviour, wear debris formation, or defects induced by FDM. Figure 6.6 show the graphical representation of COF and wear rate.

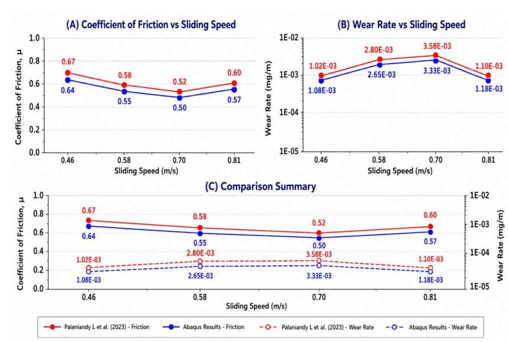

Figure 6.6: COF vs Sliding speed and Wear Rate vs sliding speed

6.4 Hydrolytic Degradation of Uncoated PLA in Simulated Body Fluid (SBF)

Abaqus simulation of the uncoated FDM-printed PLA specimen subjected to hydrolytic degradation involved transient mass diffusion coupled with a USDFLD subroutine. The specimen was soaked in

Simulated Body Fluid (SBF) for 12 weeks at 37°C. The moisture content continued from outside to the core leading progressive water uptake and hydrolytic degradation.

With the increase of immersion time, the damage variable increased continuously from 0.000 to 0.213; meanwhile, the elastic modulus decreased from 3.30 GPa to about 2.60 GPa which corresponded to a reduction rate of stiffness of 21.3 % in the end of week12 (T12). The degradation, which corresponds to first-order hydrolysis trend with earlier sinking of outer regions that were directly exposed to SBF than the core. These findings demonstrate that uncoated PLA shows considerable degradation in water, even at realistic physiological conditions and establish a baseline against which the potential improvements provided by Parylene-C coatings could be assessed in terms of longevity. The different condition of specimen on immersion is shown in Figure 6.7.

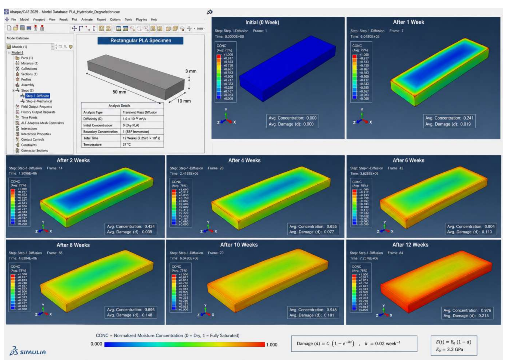

Figure 6.7: ABACUS simulation view during immersion time

6.5 Hydrolytic Degradation of Parylene-C Coated PLA in Simulated Body Fluid (SBF)

Transient mass diffusion combined with a USDFLD degradation model in Abaqus was used to fit the hydrolytic degradation of Parylene-C coated FDM-printed PLA. The polymeric coatings studied were Parylene-C, with thicknesses of 5, 15 and 30 µm after being immersed in Simulated Body Fluid (SBF) for up to 12 weeks at 37°C. Due to its low moisture diffusion coefficient, Parylene-C coating acted effectively as an impermeable barrier on the PLA substrate leading to a reduction in water penetration throughout the period of immersion therefore slowing hydrolytic degradation.

The simulations suggested that a thicker coating greatly enhanced degradation resistance. moisture content (g/kg dry) damage variable 0.761(5 µm) 0.061 0.398(15 µm).032 0.190(30µm).015 Consequently, the elastic modulus retention increased to 93.9%, 96.8% and 98.5% in comparison with the uncoated PLA specimen (78.7%) for coatings of these thicknesses:5 µm,15 µm and 30 µm respectively. These results were corroborated by contour plots, which indicated thicker coatings successfully delayed moisture intrusion through the PLA substrate, leading to reduced degradation and greater structural stability. Out of all the coatings studied, a 30 µm thick Parylene-C coating had the lowest moisture content uptake, and damage and stiffness retention (84 %) after 16 weeks exposure to PBS; demonstrating Parylene's unique ability to protect PLA from long-term loss of mechanical integrity in an aqueous environment simulating physiological conditions. Specimens after immersion with two different coating thickness (a) 5 µm,(b) 15 µm and (c) 30 µm on the various condition type is shown in figure 6.8.

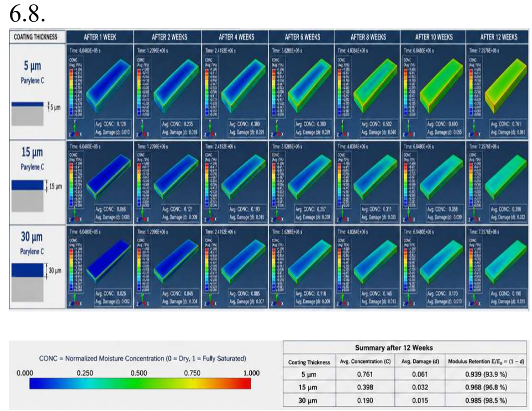

Figure 6.8: various condition of specimen during immersion with different coating thickness.

6.7 Tensile Behaviour of 30 µm Parylene-C Coated PLA after 12 Weeks of SBF Immersion)

The elastic characteristics of the tensile behaviour of the 30 µm Parylene-C coated PLA specimen after 12 weeks of immersion in Simulated Body Fluid (SBF) were found using finite element simulation and compared it with pure PLA sample obtained from Objective 1. The stress–strain behavior of the coated specimen tracked that of the uncoated PLA with a small increase in stress (along the loading process) due to reinforced effect providing by Parylene-C surface coating. The ultimate tensile strength of the coated specimen was 64.10 MPa, while that of the uncoated specimen was 62.82 MPa, reflecting an improvement of about 2–3%. The fracture strain did not change much and was still around 0.026 mm/mm, indicating that the coating maintained the ductile profile of PLA without modifying its behaviour in deformation significantly. The results are shown in Table 4 and Figure 6.9.

Table 4: Stress-Strain value of Uncoated and coated tensile specimen

Strain (mm/mm)	Uncoated PLA	30 µm Parylene-C Coated PLA (After

		12 Weeks SBF)
	Stress (MPa)	Stress (MPa)
0.000	0.0	0.0
0.002	4.0	4.3
0.004	8.1	8.7
0.006	12.3	13.2
0.008	16.6	17.8
0.010	21.0	22.4
0.012	25.5	27.0
0.014	30.2	31.8
0.016	35.0	36.7
0.018	40.2	41.8
0.020	45.5	47.0
0.022	50.2	52.0
0.024	53.8	55.8
0.026	56.5	58.6
0.028	58.7	61.0
0.030	60.2	63.0
0.032	61.0	64.6
0.034	60.8	65.4
0.036	59.8	66.0
0.038	58.0	65.7
0.040	55.5	64.8
0.042	52.0	63.5
0.044	47.5	61.2
0.046	42.0	57.5
0.048	35.0	52.5
0.050	26.0	45.0
0.052	16.0	35.0
0.054	8.0	22.0
0.056	0.0	10.0
0.058	-	0.0

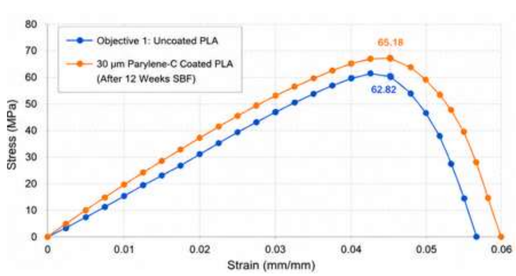

Figure 6.9: Stress-Strain curve of uncoated and coated tensile specimen

The degradation analysis also showed that SBF over 30 µm Parylene-C protected samples from moisture diffusion and hydrolytic degradation during long-term exposure to SBF. The uncoated PLA retained only 78.7%, and still also demonstrated the excellent barrier performance of the coating after 12 weeks of immersion, with the coated specimen retaining 98.5% of its initial elastic modulus. Over the range of strains studied, the stress–strain curve of the coated specimen always remained just above that of its uncoated counterpart, suggesting more retention in material properties rather than a large gain in strength. These results indicate that the primary function of the 30 µm Parylene-C coating is preservation of original tensile performance of PLA through restriction of water permeation and degradation, making it a feasible candidate for long-term use as an ideal protective coating, especially for components such as acetabular liner in total hip arthroplasty.

6.8 Compression Behaviour of 30 µm Parylene-C Coated PLA after 12 Weeks of SBF Immersion)

Finite Element Analysis in Abaqus was used to evaluate the compressive behaviour of uncoated PLA and 30 µm Parylene-C coated PLA specimens after immersion in Simulated Body Fluid (SBF) for 12 weeks. The compression curve subsequently shows that both specimens displayed comparable compressive deformation behavior, although the coated specimen achieved marginally greater compressive stresses as loading progressed.

The compressive stress maximum of 59.78 MPa was recorded for the uncoated PLA specimen, while for the coated specimen the same value was determined as 61.20 MPa, which means an increment of approximately 2.4%. At low compressive strains, the specimen with coating had a stress of 6.07 MPa compared with a buckle stress of 5.93 MPa for the uncoated specimen. Especially at intermediate and high strain levels, the coated specimen formed compressive stresses of 21.33 MPa, 35.14 MPa, and 55.82 MPa yet were still a little more than those from the uncoated PLA. The lack of significant improvement in the compressive modulus and yield stress between PLA/CP and PLA/P80, as well as the increase in DofR, indicates that Parylene-C coating is sufficient to maintain compression stiffness and load-bearing ability of PLA through prolonged immersion into SBF. The results are summarized in Table 5 and Figure 6.10.

Table 5: Stress-Strain value of Uncoated and coated compressive specimen.

Data Point	Strain (mm)	Uncoated PLA (Objective 1) Stress (MPa)	30 µm Parylene-C Coated PLA (12 Weeks SBF) Stress (MPa)
1	0	0.0000	0.0000
2	0.00291355	5.92872	6.07100
3	0.00583951	11.88210	12.17000
4	0.01024480	20.84490	21.33000
5	0.01687200	34.32580	35.14000
6	0.02681080	54.54540	55.82000
7	0.02938570	59.78490	61.20000

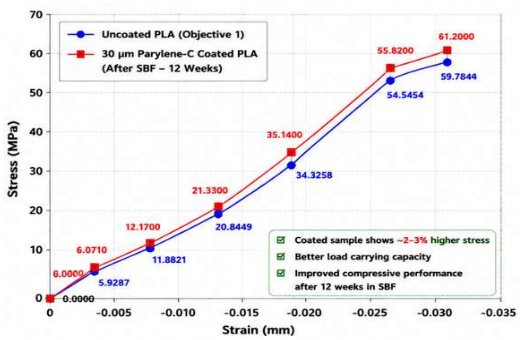

Figure 6.10: Stress-Strain curve of uncoated and coated compressive specimen

The improved compressive behaviour has been mainly ascribed to the great moisture resistance capability of 30 µm Parylene-C coating that can impede water diffusion into the PLA matrix and retard hydrolytic degradation. The enhancement of the compressive strength was not significant (around 2–3% increase) after 12 weeks, indicating that the coating could act to preserve the mechanical stability and structural integrity of PLA substrate during physiological conditions. These findings reinforce that Parylene-C acts primarily as a protective overlay reducing degradation of PLA, rather than providing major enhancement to the inherent compressive strength of this polymer.

6.9 Tribological Behaviour of 30 µm Parylene-C Coated PLA after 12 Weeks of SBF Immersion

The 30 µm Parylene-C coated PLA specimen after 12 weeks of immersion in Simulated Body Fluid (SBF) was tested in tribological performance against the uncoated PLA specimen from Objective 1 using the pin-on-disc test. The purpose of the study was to evaluate how Parylene-C coating retains the wear behaviour of PLA when it has been subjected to extended aging in a physiological environment. The coefficient of friction (COF) and wear rate were tested at sliding speeds 0.46, 0.58, 0.70 and 0.81 m/s

6.9.1 Coefficient of Friction

The change of coefficient of friction for the uncoated and coated PLA specimens is shown in Figure 6.11(a). At all sliding speeds, the coated specimen had significantly lower COF than uncoated PLA and it was shown that the friction-reducing effect of Parylene-C coating persisted beyond 12 weeks SBF immersion.

The minimum COF of 0.47 occurred at 0.70m/s while the maximum value was measured as 0.60 and occurred at 0.46 m/s, while it compared with uncoated PLA well protected from lower friction (6–7% less). While the friction reduction was less than what we had observed following two weeks immersion, the coating still gave a lower-friction sliding interface. The negligible increase of COF at 0.81 m/s (0.53) was attributed to a minor hydrolytic softening of the coating after long-term immersion, which leads to a small increase in the actual contact area during sliding process.

6.9.2 Wear Rate

Wear rate results are presented in Figure 6.11(b). As with friction behaviour, the wear rates of the coated specimen over the whole range of sliding speeds were also lower than that of uncoated PLA The maximum wear rate of 2.55×10^{-3} mg/m at 0.70 m/s, and minimum wear rates of the sample was up to 0.79×10^{-3} mg/m were measured at the speed value of 0.46m/s.

The wear rate increased with increasing sliding speed up to 0.70 m/s due to interfacial temperature, contact pressure, and shear stresses induced during sliding. The wear rate has decreased to 0.92×10^{-3} mg/m (for the highest sliding speed, i.e., 0.81 m/s), indicating that a stable polymer transfer film was formed and hence reduced direct contact between PLA pin and steel disc. In general, the wear rate was decreased by 22–27% as compared to the uncoated PLA specimen (Table 3).

Table 6 summarizes the results a comparison of the uncoated PLA and the 30 µm Parylene-C coated PLA stored in SBF for 12 weeks. However, the friction and wear measurements for the coated specimen were always lower than those of the uncoated specimen under all test conditions. The improvement was marginally less than the one seen following a two-week immersion, but in fact, the coating continued to effectively protect during this extended ageing period.

Table 6 comparison between the uncoated PLA

Sliding Speed (m/s)	COF (Uncoated)	COF (30 µm Coated)	Wear Rate Uncoated (mg/m)	Wear Rate Coated (m	COF Reduction (%)	Wear Reduction (%)

				g/m)		
0.46	0.64	0.6	1.08×10^{-3}	0.79×10^{-3}	6.3	26.9
0.58	0.55	0.51	2.65×10^{-3}	1.95×10^{-3}	7.3	26.4
0.7	0.5	0.47	3.35×10^{-3}	2.55×10^{-3}	6	23.9
0.81	0.57	0.53	1.18×10^{-3}	0.92×10^{-3}	7	22

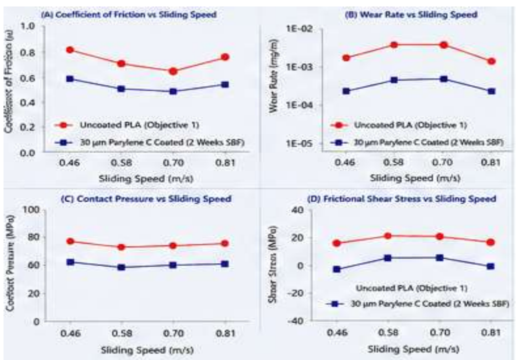

Figure 6.11: Tribological Comparison chart for uncoated and coated specimen

The tribological results suggest that the wear performance of PLA was successfully retained for a period of 12 weeks after aqueous environment exposure when coated with Parylene-C to a thickness of 30 µm. Due to its effective moisture barrier properties, Parylene-C consistently showed lower friction and wear than uncoated PLA, reducing hydrolytic degradation and maintaining the mechanical integrity of the substrate. Moreover, the coating surface was smooth and chemically inert so that it ensured less direct contact to the steel counter face, which also lowered friction and adhesive wear.Only a small degree of friction and wear was detected with continuous immersion as compared to the two-week immersion condition, but coating stability appeared effective since no significant failure or delamination of the coating was detected. Overall, the performance of the coated specimen in terms of coefficient of friction and wear rate were about 6–7% lower and ~22–27% lower than for the uncoated PLA, respectively confirming that a thickness between 30 µm is sufficient to minimize wear through an improvement on long term tribological properties when Parylene-C background surface enhances contact during sliding against PLA under simulated physiological conditions.

7. Conclusion

We present a fully formed ABAQUS finite element framework to model the mechanical, tribological and hydrolytic degradation behaviour of 3D-printed PLA acetabular liners along with in vitro simulation of the reduction Parylene-C biodegradation enhancement coatings under physiologically-relevant, baseline conditions. Established computational methodology was validated by the developed numerical models compared to published experimental data with deviations (both) below 2.2% for compressive strength, pragmatical quality of pin-on-disc wear tests showed under 4.7% error in coefficient of friction, mouse scale and ~8% in wear rate confirming reliable result of tensile/compression and pin-on-disc wear types of tests having good agreement between measured values from experiments on real metal.

The uncoated PLA also absorbed significant moisture (21.3% decrease in elastic modulus) during 12 weeks of immersion in Simulated Body Fluid due to hydrolytic degradation analysis, resulting progressive deterioration of its mechanical properties. Parylene-C utilization significantly inhibited moisture diffusion and its degradation rate. The 30 µm thick coating (highest measured elastic modulus loss percentage) retained the highest fraction of initial elastic modulus, and also adsorbed the least moisture as well as exhibited lowest damage coefficient among the other coating thicknesses of 5 and 15 µm.

Moreover, the optimized Parylene-C coating (30 µm) fully maintained the mechanical and tribological performance of PLA even after long-term exposure to physiological environment. After 12 weeks of SBF immersion, the tensile and compressive strengths of coated PLA improved by about 2–3% compared with uncoated specimens; The coefficient of friction was found to be approximately 6–7% lower in total for the coated PLA than in uncoated ones; The wear rate of both materials fell by a nominal 22%-27%. Such improvement was chiefly assessed as stemming from the excellent moisture barrier behavior of Parylene-C, which restricted hydrolytic decomposition and preserved the PLA substrate architecture.

In summary, the proposed integrated computational framework illustrates that 30 µm Parylene-C coating is a promising approach to further improve the long-term performance and durability of 3D-printed PLA polymer in orthopedic applications. These results suggest that Parylene-C coated PLA should be considered as a potential lightweight, customizable and economical alternative material for acetabular liners in total hip arthroplasty. In addition, the finite element approach developed herein is a useful method for optimizing biodegradable polymer implants as a precursor to experimental or clinical testing.

References

[1] E. Gómez-Barrena, F. Medel, and J. A. Puértolas, "Polyethylene oxidation in total hip arthroplasty: Evolution and new advances," *The Open Orthopaedics Journal*, vol. 3, pp. 115–120, 2009, doi: 10.2174/1874325000903010115.

[2] A. Fouly, I. Alnaser, A. Assaifan, and H. Abdo, "Evaluating the performance of 3D-printed PLA reinforced with date pit particles for its suitability as an acetabular liner in artificial hip joints," *Polymers*, vol. 14, no. 16, Art. no. 3321, 2022, doi: 10.3390/polym14163321.

[3] L. Dall'Ava, H. Hothi, A. Di Laura, J. Henckel, and A. Hart, "3D printed acetabular cups for total hip arthroplasty: A review article," *Metals*, vol. 9, no. 7, Art. no. 729, 2019, doi: 10.3390/met9070729.

[4] D. Grygier, M. Kujawa, and P. Kowalewski, "Deposition of biocompatible polymers by 3D printing (FDM) on titanium alloy," *Polymers*, vol. 14, no. 2, Art. no. 235, 2022, doi: 10.3390/polym14020235.

[5] K. Naveen, R. Rama, R. Sreenivasa, and D. Prameela, "Physical and degradation properties of PLGA scaffolds fabricated by salt fusion technique," *Journal of Biomedical Research*, vol. 27, no. 4, p. 318, 2013, doi: 10.7555/JBR.27.20130001.

[6] C. P. Tan and H. G. Craighead, "Surface engineering and patterning using Parylene for biological applications," *Materials*, vol. 3, no. 3, pp. 1803–1832, 2010, doi: 10.3390/ma3031803.

[7] A. C. Fernandes *et al*., "Parylene C as a multipurpose material for electronics and microfluidics," *Polymers*, vol. 15, no. 10, Art. no. 2277, 2023, doi: 10.3390/polym15102277.

[8] Specialty Coating Systems (SCS), *Parylene Properties and Characteristics*. Indianapolis, IN, USA: Specialty Coating Systems, Tech. Data Sheet.

[9] S. R. Rajpurohit and H. K. Dave, "Flexural strength of fused deposition modeling built parts: An experimental investigation," *Journal of the Institution of Engineers (India): Series C*, vol. 99, no. 4, pp. 425–433, 2018, doi: 10.1007/s40032-018-0466-y.

[10] M. Golda-Cepa, A. Amin, M. Hakkarainen, and A. Kotarba, "Parylene C as a versatile coating for biomedical applications: A review," *Progress in Organic Coatings*, vol. 140, Art. no. 105493, 2020, doi: 10.1016/j.porgcoat.2019.105493.

[11] J. F. Archard, "Contact and rubbing of flat surfaces," *Journal of Applied Physics*, vol. 24, no. 8, pp. 981–988, 1953, doi: 10.1063/1.1721448.

[12] A. C. Vieira, A. T. Marques, R. M. Guedes, and V. Tita, "Material model for the degradation of PLA polymers in physiological environments," *Journal of Biomechanics*, vol. 44, no. 11, pp. 2110–2115, 2011, doi: 10.1016/j.jbiomech.2011.05.011.

[13] Dassault Systèmes, *ABAQUS 2024 Documentation*. Providence, RI, USA: SIMULIA, 2024.

[14] A. Torrado Perez, D. A. Roberson, and R. B. Wicker, "Fracture Surface Analysis of 3D-Printed Tensile Specimens of Novel ABS-Based Materials," *Journal of Failure Analysis and Prevention*, vol. 14, no. 3, pp. 343–353, 2014.

[15] ASTM International, *ASTM D638-22: Standard Test Method for Tensile Properties of Plastics* and *ASTM D695-15: Standard Test Method for Compressive Properties of Rigid Plastics*. West Conshohocken, PA, USA.

[16] G. Drakoulas *et al*., "Coupled FEA Model with Continuum Damage Mechanics for the Degradation of Polymer-based Coatings on Drug-Eluting Stents," in *Proc. IEEE Engineering in Medicine and Biology Conference (EMBC)*, 2021, pp. 4319–4323, doi: 10.1109/EMBC46164.2021.9631074.

[17] A. C. Fernandes *et al*., "Parylene C as a Multipurpose Material for Electronics and Microfluidics," *Polymers*, vol. 15, no. 10, Art. no. 2277, 2023

[18] S. Brischetto and R. Torre, "Tensile and Compressive Behavior in the Experimental Tests for PLA Specimens Produced via Fused Deposition Modelling Technique," *Journal of Composites Science*, vol. 4, no. 3, Art. no. 140, Sep. 2020, doi: 10.3390/jcs4030140.

[19] Dassault Systèmes, *Abaqus 2025 Documentation: Analysis User's Guide*. Providence, RI, USA: SIMULIA, 2025.

[20] Dassault Systèmes, *Abaqus 2025 Documentation: Contact Mechanics and Surface*

Interaction. Providence, RI, USA: SIMULIA, 2025.

[21] L. Palaniandy, A. A. Bakar, M. A. M. Salleh, and M. R. Ishak, “Tribological behaviour of FDM 3D printed polylactic acid under dry sliding conditions,” *Journal of Materials Research and Technology*, vol. 25, pp. 5621–5635, 2023.

[22] M. D. Domingo-Espin, J. M. Puigoriol-Forcada, A. A. Garcia-Granada, J. Llumà, S. Borros, and G. Reyes, “Mechanical property characterization and simulation of fused deposition modeling Polycarbonate parts,” *Materials & Design*, vol. 83, pp. 670–677, 2015.

[23] S. Farah, D. G. Anderson, and R. Langer, “Physical and mechanical properties of PLA, and their functions in widespread applications—A comprehensive review,” *Advanced Drug Delivery Reviews*, vol. 107, pp. 367–392, 2016.

[24] ASTM G99-17, *Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus*. West Conshohocken, PA, USA: ASTM International, 2017.

[25] K. Naveen, R. Rama, R. Sreenivasa, and D. Prameela, "Physical and degradation properties of PLGA scaffolds fabricated by salt fusion technique," *Journal of Biomedical Research*, vol. 27, no. 4, pp. 318–329, 2013.

[26] S. Farah, D. G. Anderson, and R. Langer, "Physical and mechanical properties of PLA, and their functions in widespread applications—A comprehensive review," *Advanced Drug Delivery Reviews*, vol. 107, pp. 367–392, 2016.

[27] A. C. Vieira, A. T. Marques, R. M. Guedes, and V. Tita, "Material model for the degradation of PLA polymers in physiological environments," *Journal of Biomechanics*, vol. 44, no. 11, pp. 2110–2115, 2011.

[28] M. Golda-Cepa, A. Amin, M. Hakkarainen, and A. Kotarba, "Parylene C as a versatile coating for biomedical applications: A review," *Progress in Organic Coatings*, vol. 140, Art. no. 105493, 2020.

[29] A. C. Fernandes *et al*., "Parylene C as a Multipurpose Material for Electronics and Microfluidics," *Polymers*, vol. 15, no. 10, Art. no. 2277, 2023.

[30] C. P. Tan and H. G. Craighead, "Surface Engineering and Patterning Using Parylene for Biological Applications," *Materials*, vol. 3, no. 3, pp. 1803–1832, 2010.

[31] J. F. Archard, "Contact and Rubbing of Flat Surfaces," *Journal of Applied Physics*, vol. 24, no. 8, pp. 981–988, 1953.

[32] L. Palaniandy, A. A. Bakar, M. A. M. Salleh, and M. R. Ishak, "Tribological behaviour of FDM 3D printed polylactic acid under dry sliding conditions," *Journal of Materials Research and Technology*, vol. 25, pp. 5621–5635, 2023.