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3D-Printing of Thermoplastic Polyurethane (TPU) : A comprehensive review of properties, applications, and challenges

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Abstract

The advent of additive manufacturing has revolutionized the field of materials science, allowing the making of intricate geometries and customized products. Among the various materials used in 3D printing, Thermoplastic Polyurethane (TPU) has emerged as a promising candidate due to its unique properties, including flexibility, elasticity, and resistance to abrasion and chemicals. This review paper provides a wide-ranging outline of the properties, applications, and challenges associated with 3D printing of TPU. The paper begins with an introduction to additive manufacturing of flexible materials, highlighting the benefits of TPU in various industries, including sealing, medical devices, and tissue engineering. The review then delves into the Fused Deposition Modelling (FDM) of TPU filaments, including the parameters that affect TPU printing and their impact on mechanical properties. The paper also examines the applications of 3D-printed TPU in numerous grounds, including sealing, medical devices, and tissue engineering. Furthermore, the review identifies the challenges and future scope of TPU 3D printing, including material limitations, printing defects, and post-processing techniques. The paper also discusses the current research trends and upcoming guidelines in TPU 3D printing, including the development of new TPU formulations, optimization of printing parameters, and integration of TPU with other materials. This comprehensive review aims to provide a valuable resource for investigators, technologists, and creators seeking to understand the potential and limitations of TPU 3D printing.

Keywords: Thermoplastic polyurethane (TPU), material properties, printing parameter, sealing applications

Introduction

Additive manufacturing (AM), also known as 3D printing, has revolutionized manufacturing by enabling the creation of complex geometries directly from digital designs, layer by layer. While initially used for rapid prototyping, AM is increasingly employed for producing functional end-use parts across various industries [1]. A significant area of growth within AM is the processing of flexible materials, which unlocks new possibilities for applications requiring elasticity, compliance, and adaptability [2].

Flexible materials, including thermoplastic polyurethanes (TPUs), elastomers, and other soft polymers, present unique challenges and opportunities in AM. Traditional manufacturing methods for these materials, such as molding and casting, can be limited in their ability to produce intricate designs or customized parts in small quantities [3].

AM offers several advantages for flexible materials

- **Design Freedom:** AM allows for the making of intricate geometries, including lattice structures, variable densities, and integrated components, which can be optimized for specific mechanical properties.
- **Customization:** AM allows the making of tailored parts with specific shapes, sizes, and properties, catering to individual needs and low-volume production.
- **Material Efficiency:** AM methods typically involving less material waste compared to subtractive manufacturing methods [4].
- **Rapid Prototyping and Iteration:** AM facilitates rapid design iterations, allowing for faster development and testing of flexible components.

The ability to process flexible materials with AM has led to innovations in diverse fields. In biomedical engineering, AM is used to create customized prosthetics, orthotics, and soft robotics [5]. In the automotive and aerospace industries, AM enables the production of lightweight, vibration-damping components and seals. The footwear and sporting equipment sectors benefit from AM's capability to produce customized shoes, cushioning elements, and protective gear [6].

Among the flexible materials used in AM, thermoplastic polyurethane (TPU) is of particular interest due to its excellent combination of properties, including high elasticity, abrasion resistance, tear strength, and chemical resistance. This review will focus on the additive manufacturing of thermoplastic polyurethane (TPU), its properties, processing techniques, and its application in sealing and medical field.

Properties of thermoplastic polyurethane for sealing applications

Thermoplastic polyurethane (TPU) is a versatile class of elastomeric polymers that exhibit a unique combination of properties, making them attractive for a wide range of applications, including industrial sealing. Their performance in sealing applications is determined by a complex interplay of several key characteristics.

Chemical structure and Composition

TPUs are block copolymers comprise of alternating sequences of hard and soft segments. The hard segments, typically formed from the reaction of diisocyanates with short-chain diols (chain extenders), provide stiffness, strength, and thermal stability. The soft segments, derived from long-chain diols (polyols), contribute to the material's flexibility, elasticity, and low-temperature performance [7].

The specific chemical composition of the hard and soft segments can be tailored to achieve a wide range of properties. Common diisocyanates include methylene diphenyl diisocyanate (MDI) and toluene diisocyanate (TDI). Polyester polyols offer excellent tensile strength, tear resistance, and oil resistance, while polyether polyols provide superior hydrolysis resistance and low-temperature flexibility [7].

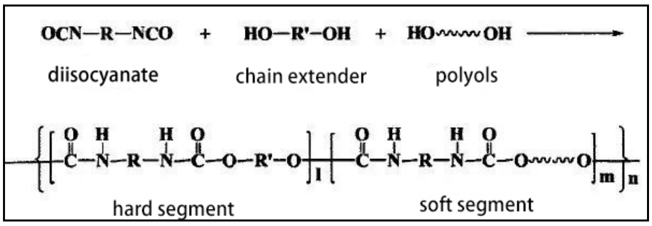

Fig 1: Chemical Structure of Thermoplastic Polyurethane

Key properties for Sealing

Several properties make TPU particularly well-suited for sealing applications:

- **Elasticity and Flexibility:** Seals must conform to mating surfaces and maintain contact under varying conditions. TPU's inherent elasticity and flexibility allow it to deform and recover, ensuring a tight seal even with surface irregularities or dimensional changes due to temperature or pressure [8]. This is often quantified by properties like elongation at break and Young's modulus.

- **Compression Set:** A critical property for seals is compression set, which measures the extent to which a seal permanently deforms under compressive load. A low compression set is essential to ensure that the seal maintains its sealing force over time. TPU formulations can be designed to exhibit excellent compression set resistance [9].

- **Abrasion and Wear Resistance:** Seals in dynamic applications, such as rotary seals or hydraulic cylinders, are subjected to friction and wear. TPU possesses high abrasion and wear resistance, enabling it to withstand these harsh conditions and maintain its sealing performance over extended periods.

- **Tear Strength:** Seals can be subjected to tearing forces during installation or in service, especially around sharp edges or corners. TPU's high tear strength prevents crack propagation and ensures seal integrity [10].

- **Chemical Resistance:** Industrial seals often come into contact with a variety of fluids, including oils, fuels, solvents, and hydraulic fluids. TPU can be articulated to exhibit excellent resistance to a wide range of chemicals, preventing swelling, degradation, and loss of sealing performance. The specific chemical resistance depends on the TPU's chemical composition (e.g., ester-based TPUs generally have better oil resistance than ether-based TPUs).

- **Temperature Resistance:** Seals may operate over a widespread temperature range, from low temperatures where flexibility is required to high temperatures where thermal stability is crucial. TPU materials can be selected to maintain their properties over a wide temperature range [11].

- **Hydrolysis Resistance:** In applications involving water or humid environments, seals must resist degradation due to hydrolysis. Ether-based TPUs generally offer superior hydrolysis resistance compared to polyester-based TPUs.

Tailoring TPU properties

The properties of TPU can be personalized by adjusting the ratio of hard to soft segments, the type of diisocyanate and polyol used, and the addition of additives. This tunability allows TPU to be optimized for specific sealing requirements. For example, a higher hard segment content will increase stiffness and hardness, while a higher soft segment content will enhance flexibility and elasticity [12].

This ability to tailor TPU properties, combined with the design freedom offered by additive manufacturing, unlocks new possibilities for creating high-performance seals with optimized geometries and material properties.

FDM parameters affecting TPU printing

The Fused Deposition Modelling (FDM) process involves several key parameters that significantly influence the successful printing of Thermoplastic Polyurethane (TPU) and the final part's properties. Optimizing these parameters is crucial for achieving the desired dimensional accuracy, surface finish, and mechanical performance of TPU seals [13].

Key FDM Parameters and Their Influence on TPU Printing

1. Filament Feeding

TPU's flexibility makes it prone to buckling and tangling during feeding. Direct-drive extruders, with the feeding mechanism close to the nozzle, are generally preferred over Bowden extruders (where the mechanism is further away) for TPU. Consistent filament diameter with a tolerance of ± 0.05 mm and minimal variations are essential for uniform extrusion [14].

2. Extrusion Temperature

TPU has a comparatively low melting temperature range, but it's critical to balance melt flow with solidification. Too low a temperature leads to high viscosity, poor layer adhesion, and potential clogging. Too high a temperature results in excessive flow, stringing, oozing, and potential thermal degradation of the TPU. The optimal temperature depends on the specific TPU grade, its melt flow index, and the printer's thermal characteristics with a typical range 190-230 °C [15].

3. Print Speed

Print speed and extrusion rate must be coordinated. Slower speeds allow more time for layer bonding and can improve dimensional accuracy, especially for flexible materials like TPU. Faster speeds can reduce print time but may lead to under-extrusion, poor layer adhesion, and a rougher surface finish. Optimum print speed range of 20-50 mm/s gave promising results [16].

4. Layer Height

Layer height affects the vertical resolution of the print. Thinner layers improve surface finish and capture finer details but increase print time [17]. Thicker layers increase print speed but may reduce dimensional accuracy and layer adhesion. The test results were focused around layer heights in range between 0.1-0.3 mm

5. Flow Rate

This parameter controls the amount of material extruded. Proper calibration is crucial for TPU to avoid under-extrusion (gaps, weak layers) or over-extrusion (excess material, blobs). Here the range to get optimum mix of good dimensional accuracy, layer adhesion and preventing defects lies between 90-110% [18].

6. Cooling

Controlled cooling is essential for TPU to manage its viscoelastic behaviour. Too rapid cooling can cause warping and delamination, especially with larger parts. Insufficient cooling can lead to excessive deformation and loss of dimensional accuracy. The FDM printer fan speed range between: 0-50% and surrounding temperature 20-40°C gave good results [19].

7. Build Plate Adhesion

Proper adhesion of the first layer to the build plate is critical for successful TPU printing. Techniques include using a heated build plate, applying adhesives (glue), or using specific build plate surfaces (Polyetherimide, glass). To prevent detachment, warping and proper first layer bonding build plate temperature should be in range of 40-60 °C [20].

8. Infill Density and Pattern

Infill density affects the internal structure and stiffness of the part. For seals, the infill design and density can be optimized to balance flexibility and structural integrity under compression. Common patterns include grid, concentric, and gyroid. To get satisfactory results for sealing and medical applications infill density was known to be set between 20-50%.

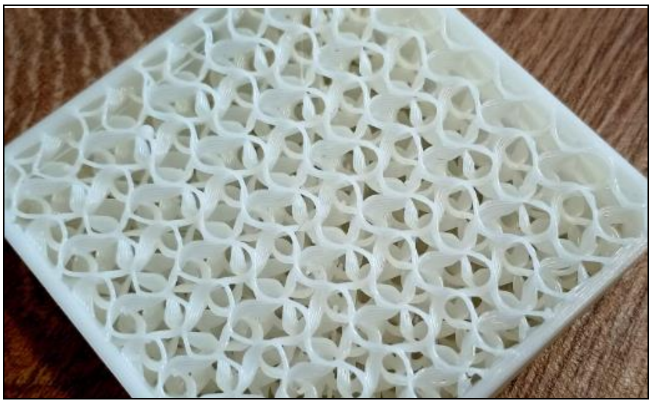

Fig 2: Gyroid Infill Pattern

Retraction

Retraction involves pulling the strand back into the nozzle when the printer moves between printing segments. Optimizing retraction settings is crucial for TPU to minimize stringing and oozing, which can affect the seal's surface quality and performance [13]. Results were majorly focused around retraction distance in range of 1 to 5 mm and speed of retraction with minimum of 20 mm/s to maximum of 40 mm/s.

Table 1: Optimum Fdm Parameters For TPU

Sr No	Parameter	Value Range	Unit
1	Filament feeding	1.75 ±0.05	mm
2	Extrusion Temperature	190-230	°C
3	Print Speed	20-50	mm/s
4	Layer Height	0.1-0.3	mm
5	Flow rate	90-110	%(Percentage)
6	Cooling (Fan Speed)	0-50	%(Percentage)
7	Build Plate temperature	40-60	°C
8	Infill Density & Pattern	20-50	%(Percentage)
9	Retraction	20-40	mm/s

Mechanical Properties of 3D-Printed TPU for Sealing and Medical Applications

The mechanical properties of 3D-printed TPU parts are crucial for their performance in sealing and medical applications. These properties are influenced by the TPU material itself, the 3D printing process parameters, and the specific design of the part.

The FDM process can influence these mechanical properties [21]. For example, layer adhesion can affect tensile strength and elongation, while printing orientation can affect anisotropy.

a. Property Requirements for sealing and medical applications

High elongation at break and low compression set are critical for maintaining a tight seal. While Good tear strength and wear resistance are important for dynamic seals [22]. Moreover, chemical resistance to the sealed fluid is also essential. In the case of medical application biocompatibility and sterilizability are mandatory. Mechanical properties must be tailored to match the specific application (e.g., high flexibility for wearable devices, high strength for implants). Meanwhile low friction may be desirable for devices in contact with tissue or other materials [23].

b. Key Mechanical Properties

1. Hardness

Typically measured using Shore durometer scales (Shore A or D). Indicates the material's resistance to indentation. Values for sealing and medical applications often range from Shore A 70 to Shore D 60, depending on the required flexibility and stiffness. Lower Shore A values indicate a softer, more flexible material, while higher Shore D values indicate a harder, more rigid material [24].

2. Tensile Strength

Measures the material's resistance to breaking under tension. Important for seals to withstand pressure and for medical devices to withstand physiological loads. Values can range from 10 to 50 MPa, depending on the TPU grade and printing parameters [25].

3. Elongation at Break

Calculates the material's capacity to stretch before failing completely. Critical for seals to conform to mating surfaces and for flexible medical devices. TPU can exhibit high elongation at break, often in the range of 200% to 800%.

4. Tear Strength

Measures the material's resistance to tearing. Important for seals to prevent damage during installation and use, and for medical devices to withstand tearing forces. Values typically range from 20 to 100 kN/m [26].

5. Compression Set

Measures the material's capacity to return to its original shape later being compressed. A low compression set is crucial for seals to maintain sealing force over time. Values are expressed as a fraction, with lower values indicating better performance (e.g., <20% after 24 hours at room temperature).

6. Flexural Modulus

Measures the material's resistance to bending. Important for seals and medical devices that need to flex or bend in service. Values can range from 10 to 1000 MPa, depending on the TPU grade [26].

c. Friction and Wear Properties

1. Coefficient of Friction:

Describes the resistance to sliding between two surfaces. Important for dynamic seals to minimize friction and wear, and for medical devices in contact with other surfaces [27]. TPU generally has a moderate coefficient of friction, which can be modified with additives or surface treatments. The coefficient of friction of 3d Printed TPU falls in the range of 0.2 to 0.7.

2. Wear Resistance

Measures the material's capacity to survive wear due to friction. Crucial for dynamic seals to ensure long service life. TPU exhibits good wear resistance, which can be further enhanced by optimizing the material formulation and printing parameters. The Volume loss is in the range of 10 to 50 mm³/N·m [28].

Table 2: Mechanical & Friction Properties Requirement

Sr No	Property	Value Range	Unit
1	Hardness	A-70 to D-60	Shore
2	Tensile Strength	10 to 50	MPa
3	Elongation at Break	200-800	%(Percentage)
4	Tear Strength	20 to 100	kN/m
5	Compression Set (24 Hrs.)	Less than 20	%(Percentage)
6	Flexural Modulus	10 to 1000	MPa
7	Coefficient of Friction	0.2-0.7	-
8	Wear Resistance	10 to 50	mm³/N·m

Applications of 3D-Printed TPU

Thermoplastic polyurethane (TPU) is a multipurpose material, and when combined with the capabilities of additive manufacturing (AM), it opens up a wide range of application possibilities [29]. This chapter will explore the existing and probable applications of 3D-printed TPU, with a particular focus on sealing applications and related areas.

a. Sealing Applications

The properties of TPU, such as its flexibility, elasticity, and chemical resistance, make it an attractive candidate for various sealing applications [30]. AM, particularly FDM, offers the ability to produce custom seals with intricate geometries and tailored properties.

- **Static Seals:** 3D-printed TPU can be used to create static seals, such as gaskets, that are used between stationary parts. AM allows for the production of gaskets with complex shapes and varying thicknesses to conform to uneven surfaces and provide a tight seal [31].

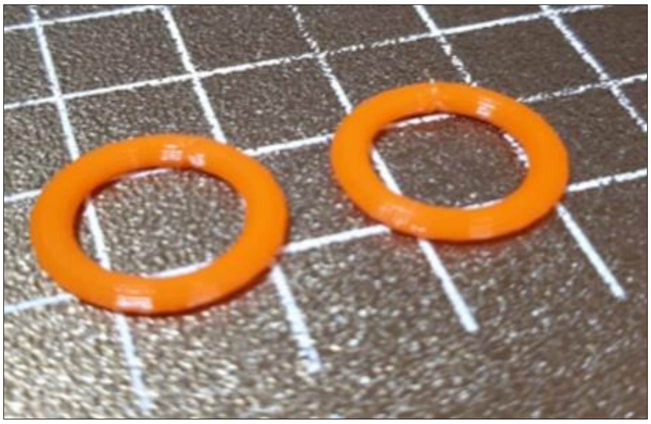

Fig 3: Rubber Gasket for Garden Hose Pipe

- **Dynamic Seals:** Dynamic seals, such as O-rings and lip seals, are used between moving parts. 3D-printed TPU can offer advantages in these applications, including the ability to create custom designs with optimized friction and wear properties. The potential for on-demand production of replacement seals is also a significant advantage.

- **Custom Seals:** AM's ability to produce highly customized parts is particularly beneficial in sealing applications where standard seals are not suitable [32]. This includes applications with unique shapes, sizes, or operating conditions.

- **Tooling for Seal Production:** 3D-printed TPU can also be used to create tooling, such as molds and fixtures, for the production of traditional seals [33]. This can reduce lead times and costs, especially for low-volume production [34].

b. Medical Applications

TPU's biocompatibility, flexibility, and sterilizability make it suitable for various medical applications, and AM enhances its potential in this field [35].

- **Prosthetics and Orthotics:** 3D-printed TPU can be used to create custom prosthetics and orthotics with improved comfort, fit, and functionality. The ability to tailor the stiffness and flexibility of the TPU material allows for the creation of devices that better mimic human tissue.

- **Surgical Models and Guides:** 3D-printed TPU can be used to create realistic surgical models for pre-surgical planning and simulation. It can also be used to make surgical guides that improve the accuracy and precision of surgical procedures.

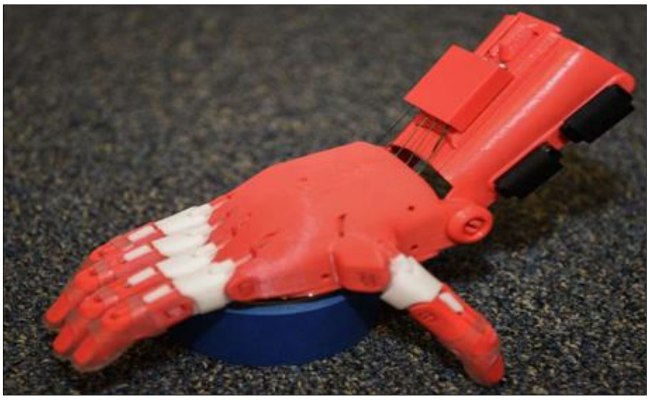

Fig 4: 3D Printed TPU Prosthetic Hand

- **Drug Delivery Devices:** The ability to create complex geometries with AM allows for the development of different drug delivery devices using TPU. This includes implants with controlled release properties and customized shapes.

- **Wearable Medical Devices:** TPU's flexibility and durability make it suitable for wearable medical devices, such as sensors and monitoring devices [36]. AM enables the production of customized devices that conform to the patient's body and provide improved comfort and performance.

c. Other Applications

Beyond sealing and medical, 3D-printed TPU finds applications in a variety of other fields:

- **Automotive:** TPU is used in the automotive industry for applications such as gaskets, seals, hoses, and vibration damping components. AM allows for the production of these parts with customized designs and improved performance.

- **Aerospace:** In the aerospace industry, TPU can be used for seals, gaskets, and other flexible components that require high performance and reliability. AM can enable the production of lightweight and complex parts.

- **Consumer Goods:** 3D-printed TPU is used in the production of consumer goods such as footwear, sportswear, and protective gear. AM allows for the creation of customized products with improved comfort, performance, and aesthetics.

Challenges and Future Scope

Despite the significant potential of 3D-printed TPU, several challenges remain that need to be addressed to further expand its applications, particularly in sealing and medical fields [37].

a. Challenges

- **Dimensional Accuracy and Consistency:** Achieving high dimensional accuracy and part-to-part consistency with FDM-printed TPU can be challenging due to the material's flexibility and the process's inherent variability. Warping, shrinkage, and other deformations can occur, especially with complex geometries [38].

- **Surface Finish:** The layer-by-layer nature of FDM often results in a relatively rough surface finish, which may not be suitable for all sealing and medical applications. Post-processing techniques, such as sanding, coating, or chemical smoothing, can improve surface finish but add complexity and cost [39].

- **Mechanical Properties:** While TPU possesses desirable mechanical properties, the FDM process can sometimes reduce these properties compared to traditionally manufactured parts. For example, layer adhesion can be a limiting factor for tensile strength, and anisotropy can affect overall performance [17].

- **Printing Speed:** Printing with flexible TPU can be slower than with rigid materials due to the need for careful control of extrusion speed and cooling. This can limit the scalability of FDM for high-volume production [20].

- **Material Range:** While a variety of TPU materials are available, the range of TPU formulations specifically optimized for FDM is still relatively limited. The development of new TPU materials with improved printability and performance would expand application possibilities [40].

- **Regulatory and Validation:** In the medical field, the use of 3D-printed TPU is subject to stringent regulatory requirements. Validating the safety, efficacy, and long-term performance of 3D-printed TPU medical devices can be a complex and time-consuming process [41].

b. Future Scope

Despite these challenges, the future of 3D-printed TPU is promising. Ongoing research and development efforts are focused on addressing the current limitations and expanding the technology's capabilities [42].

- **Advanced Materials:** The development of new TPU formulations with enhanced printability, mechanical properties, and biocompatibility will be a key area of focus. This includes TPUs with improved thermal stability, reduced moisture sensitivity, and tailored biodegradation rates [43].

- **Process Optimization:** Continued research into optimizing FDM process parameters for TPU will lead to improved dimensional accuracy, surface finish, and mechanical properties. This includes the use of advanced control systems, adaptive printing strategies, and real-time monitoring [44].

- **Multi-Material Printing:** Combining TPU with other materials in a single print could enable the creation of new devices and systems with enhanced functionality. For example, combining TPU with rigid materials could create seals with integrated support structures or medical devices with varying degrees of flexibility [45].

- **Post-Processing Techniques:** The development of more efficient and effective post-processing techniques will be crucial for improving the surface finish and properties of 3D-printed TPU parts. This includes automated sanding, chemical vapor smoothing, and advanced coating technologies.

- **Emerging AM Technologies:** While FDM is currently the most common AM technology for TPU, other technologies, such as selective laser sintering (SLS) and material jetting, may offer advantages in terms of resolution, accuracy, and material properties. Further research into these technologies for TPU processing is warranted [46].

- **Smart and Responsive Materials:** The integration of smart and responsive materials with 3D-printed TPU could lead to the development of new devices with adaptive properties. For example, TPU with embedded sensors could be used to create self-monitoring seals or wearable medical devices with dynamic responses.

Conclusion

This review paper has provided a comprehensive overview of the properties, applications, and challenges associated with 3D printing of Thermoplastic Polyurethane (TPU). The unique properties of TPU make it an attractive material for various industries, including sealing, medical devices, and tissue engineering. However, the review has also highlighted the challenges and limitations associated with TPU 3D printing, including material limitations, printing defects, and post-processing techniques. To overcome these challenges, further research is needed to develop new TPU formulations, optimize printing parameters, and integrate TPU with other materials. The findings of this review paper have significant implications for researchers, engineers, and manufacturers seeking to understand the potential and limitations of TPU 3D printing and to develop innovative products and solutions.

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