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TRENDS IN THE USE OF PLASTIC MATERIALS IN 3D PRINTING APPLICATIONS

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Abstract: *The article proposes an analysis of the most recent articles in the field of 3D printing applications of hard plastic parts made using FDM and FFF technologies. It analyzes the materials used in applications considering their characterization according to several criteria, such as Tensile Strength, Heat Resistance, Chemical Resistance, Cost, Ease of 3D Printing, Dimensional stability (Coefficient of Thermal Expansion, Moisture Absorption), Hardness. Related visual aspects of the studied 3D printed materials (Surface Quality, Color Availability, Translucency, and Appearance) are also analyzed. Some conclusions drawn from research conducted by various authors regarding the ranking of the studied materials according to certain parameters are presented. The researched bibliographic sources are presented in a central table grouped by common topics subdivided into specific topics. The common topics considered are mechanical properties, process parameters, applications, and reviews. Articles in the field of material applications in FDM part manufacturing are described and critically analyzed in more detail, being grouped by specific topics, such as tribological applications, 3D-Printed Gears, Aerospace Applications, Automotive Applications, Molds and Dies, Multi-Materials. A special chapter is dedicated to review/overview articles, being described articles with specific topics from the point of view of application fields, such as 3D printing of polymers, Industry 4.0, Industry 4.0 and 3D Printing, Industry 5.0 Innovations, Limitations of 3D printing, technologies. The article presents some more important conclusions of the critical analyses of the studied bibliographic sources.*

Key words: *3D Printing, Fused Deposition Modeling (FDM), Thermoplastics, Comparative analysis, Main parameters, Mechanical properties, Process parameters, Applications.*

1. INTRODUCTION

3D printing has revolutionized manufacturing by enabling rapid prototyping and customized production. Hard plastics play a crucial role in this domain, offering a balance of strength, durability, and resistance to environmental factors. This review examines various hard plastic materials used in 3D printing, their properties, applications, and printing challenges, integrating key findings from recent research and publications [1] [2] [3] .

The selection of appropriate materials is essential for ensuring the success of 3D-printed components. Factors such as mechanical strength, chemical and thermal resistance, and cost-effectiveness must be considered. This review focuses on commonly used hard plastics in 3D printing, evaluating their properties, applications, and printing considerations based on recent studies [4] [5] [6].

2. CLASSIFICATION OF HARD PLASTICS

Hard plastics used in 3D printing are broadly classified into thermoplastics and thermosets.

- *Thermoplastic materials* soften upon heating and harden when cooled, making them suitable for multiple heating cycles. Examples include PEI, PC, ABS, Nylon, and PEEK [7].
- *Thermosets* undergo irreversible curing upon heating and cannot be remelted. Although less common in 3D printing, some specialized applications use thermoset resins [8].

Common properties of hard plastics include high mechanical strength, good chemical resistance, and suitability for a range of applications in aerospace, automotive, medical, and industrial sectors [9] [10].

2.1. Polylactic Acid (PLA)

PLA is a biodegradable thermoplastic derived from renewable resources like cornstarch or sugarcane. Its eco-friendly nature and favorable properties have made it a popular choice in various industries, particularly in 3D printing [11].

- *Properties* [12]:

PLA can decompose into natural elements under industrial composting conditions. It offers good tensile strength and stiffness, suitable for applications requiring structural integrity. However, PLA is more brittle compared to some other plastics. PLA has a relatively low melting point between 150 °C to 160 °C, which facilitates easy processing and lower heat resistance. In pure form, PLA can be transparent, allowing for

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applications with clarity. PLA is resistant to moisture and UV light but can be broken down by microorganisms, contributing to its biodegradable characteristic.

- *Applications*:

PLA is widely used as a filament in fused deposition modeling (FDM) 3D printing due to its low melting point, minimal warping, and ease of use.

1. Its safety, clarity, and moisture resistance make PLA suitable for food packaging, including containers, cups, films, and bottles.

2. Due to its biocompatibility, PLA is used in medical implants like stents and implantable drug dispensers designed to biodegrade over time.

- *3D Printing Considerations*: PLA is easy to print with low warping, typically extruded at (190 to 220) °C and bed temperatures of 0–60 °C. It adheres well to glass or PEI surfaces, requiring minimal adhesion aids. No special printer requirements are needed, and active cooling improves print quality. However, PLA is brittle and unsuitable for high-temperature or impact-resistant applications.

2.1. Polyetherimide (PEI)

Polyetherimide (PEI) is a high-performance thermoplastic polymer known for its excellent thermal stability, mechanical strength, and chemical resistance. It is widely used in engineering applications where heat resistance and durability are critical. PEI is often used in 3D printing, particularly in FDM, under the commercial name Ultem with its variants Ultem 9085 and Ultem 1010 [54] [55]. Variants of composite Ultem with glass fibers used for their increased stiffness, reduced impact resistance, and carbon fibers having High strength-to-weight ratio [56].

- *Properties*: High-temperature resistance (up to 220 °C continuous use), high tensile strength (85–100 MPa), excellent chemical resistance to hydrocarbons, acids, and solvents, inherent flame retardancy (UL 94 V-0 rating), and good dimensional stability under thermal cycling [10] [57] [58].
- *Applications*: Polyetherimide (PEI) is widely utilized across multiple industries due to its exceptional mechanical strength, thermal stability, and chemical resistance. In the aerospace sector, PEI is employed in structural components, lightweight panels, and high-temperature insulation parts, ensuring durability in extreme environments (Ultem 9085). In the automotive industry, PEI is used for under-the-hood applications, electrical connectors, and lightweight reinforced parts, enhancing vehicle efficiency and safety. In the medical field, PEI is valued for its biocompatibility and sterilization resistance, making it suitable for surgical instruments, dental prosthetics, and diagnostic equipment (Ultem 1010) [13].
- *3D Printing Considerations*: Requires high extrusion temperatures (~ 350 °C), prone to warping, benefits from a heated chamber [14] [15].

2.2. Polycarbonate (PC)

- *Properties*: High impact resistance (Izod impact strength of up to 850 J/m), excellent optical clarity with over 90% light transmission, good heat resistance with a glass transition temperature of approximately 147 °C, and inherent flame retardancy (UL 94 V-2 rating) [16].
- *Applications*: Polycarbonate (PC) is widely utilized due to its high impact resistance and optical clarity. In protective gear, it is used for helmets, face shields, and safety goggles, ensuring durability and shatter resistance. In the automotive sector, PC is employed in headlamp lenses, instrument panels, and lightweight structural components, contributing to vehicle safety and efficiency. Additionally, in electrical applications, PC serves as an insulating material for electrical housings, switchgear enclosures, and LED lighting covers, providing flame retardancy and mechanical stability [16].
- *3D Printing Considerations*: Requires high printing temperatures (~ 260 °C), prone to warping, best printed in an enclosed chamber [6].

2.3. Acrylonitrile Butadiene Styrene (ABS)

- *Properties*: Toughness, ease of processing, moderate heat resistance (glass transition temperature of ~ 105 °C), good impact resistance (Izod impact strength of ~ 300 J/m), and fair chemical resistance to oils and greases [17].
- *Applications*: Acrylonitrile Butadiene Styrene (ABS) is extensively used in various sectors due to its toughness, ease of processing, and impact resistance. In consumer products, ABS is found in household appliances, toys, and electronic casings, benefiting from its lightweight and durable properties. For prototyping, ABS is a preferred material in rapid manufacturing due to its affordability and ease of post-processing, allowing for smooth finishes and structural modifications. In the automotive industry, ABS is commonly used for interior and exterior trim parts, dashboards, and bumper reinforcements, where its mechanical properties contribute to both aesthetic and functional requirements [18].
- *3D Printing Considerations*: Prone to warping, requires a heated bed (~ 100 °C), releases fumes, can be post-processed with acetone [19].

2.4. Polyamide (Nylon)

- *Properties*: High durability, flexibility, excellent wear resistance, low friction coefficient, good impact strength, and moderate chemical resistance to oils and solvents [20].
- *Applications*: Polyamide (Nylon) is widely used in various industries due to its durability, flexibility, and excellent wear resistance. In mechanical engineering, it is employed in the production of gears, bushings, and bearings, benefiting from its low friction coefficient and self-lubricating properties, which reduce wear and extend component lifespan. In the automotive sector, Nylon is used in fuel lines, cable ties, and engine covers due to its resistance to chemicals and high temperatures. Additionally, in consumer electronics, it is utilized for durable casings and structural components, ensuring impact resistance and longevity. Functional prototypes made from Nylon provide engineers with high-fidelity test

models, allowing for performance validation before mass production [21].

- *3D Printing Considerations*: Polyamide (Nylon) is highly hygroscopic, necessitating dry storage and pre-printing drying to prevent print defects. It is compatible with both FDM and SLS printing, offering high strength and flexibility. However, it requires high extrusion temperatures (~ 250 °C) and a heated bed (~ 60 °C) for optimal adhesion. SLS printing of Nylon benefits from precise laser sintering, enabling complex geometries with excellent mechanical properties.

2.5. Co-Polyester (CPE)

CPE is a strong, chemical-resistant, and durable 3D printing filament. It is similar to PETG but offers higher impact strength and better chemical resistance. CPE is often used in industrial, engineering, and functional applications due to its toughness and temperature resistance [22].

- *Applications*:

CPE is used when needed a strong, chemical-resistant filament that is easier to print and works well for general-purpose functional parts.

1. Industrial and engineering parts: chemical-resistant enclosures, functional prototypes, and machine components.
2. Medical and food-safe applications: food and medical equipment.
3. Automotive components: durable and heat-resistant under-the-hood parts.
4. Electronics casing: resistant to heat and chemicals protective housings.

- *3D Printing Considerations*: CPE is moderately easy to print, requiring an extrusion temperature of (230 to 250) °C and a heated bed around (80 to 100) °C. It has low warping and good adhesion to surfaces like PEI or Kapton tape. CPE benefits from a heated chamber but does not require special printer modifications.

2.6. Co-Polyester Plus (CPE+)

CPE+ is an enhanced version of standard CPE, offering better mechanical and thermal properties. It is designed for higher-strength applications, improved heat resistance, and lower warping compared to standard CPE

- *Applications*:

CPE+ is used for higher strength, better heat resistance, and improved durability for industrial-grade, load-bearing applications.

1. High-Strength Functional Parts used in engineering applications requiring superior mechanical performance.
2. Automotive Components. Better heat and chemical resistance makes it ideal for under-the-hood or high-temperature environments.
3. Stronger and tougher industrial prototypes and machine parts, reducing wear and tear.
4. Protective casings for electronics that withstands higher temperatures and impacts compared to standard.
5. Chemical-resistant components offering superior resistance to chemicals, solvents, and UV exposure.

- *3D Printing Considerations*: It requires an extrusion temperature of (250 to 270) °C and a heated bed around (90 to 110) °C. Like CPE, it has low warping and good adhesion to surfaces like PEI. It may require a heated chamber for optimal results but is more challenging to print than standard CPE.

2.7. Polypropylene (PP)

PP is a lightweight, flexible, and chemically resistant thermoplastic widely used in industrial and consumer applications. It is known for its high impact strength, fatigue resistance, and low density, making it a great choice for applications requiring durability and flexibility [23] [24].

- *Applications*:

PP is a versatile 3D printing material with applications in automotive, medical, industrial, and consumer products. While it is challenging to print, its chemical resistance, flexibility, and durability make it ideal for specialized functional parts. When printed correctly, PP offers unique benefits over PLA, PETG, and ABS.

1. Automotive Industry: dashboards, door panels, and trim parts; electrical enclosures; fuel tanks and fluid storage; custom prototypes and spare parts.
2. Medical and healthcare: sterilizable medical equipment surgical; trays and lab containers; prosthetics and orthotic devices; face shields and respirator components.
3. Food and beverage industry: reusable food containers & bottles; cups, cutting boards, and strainers; lightweight, durable caps, lids, and protective packaging materials.
4. Industrial and chemical applications: pipes and valves; chemical-resistant storage tanks; machine components and gears (moving parts like bushings and clips); flexible hinges; living hinges (flip-top lids).
5. Consumer products and electronics: hone and smartwatch cases; storage bins and organizers; safe, flexible toys and protective gear; jewelry, bags, and footwear components.
6. Aerospace and defense: lightweight structural components; delicate electronic components in aviation; drone housings and landing gear.
7. Marine and outdoor applications: waterproof and buoyant parts; paddles, seats, and protective coverings; outdoor storage and chairs.

- *3D Printing Considerations*: PP requires an extrusion temperature of (220 to 250) °C and a heated bed around (80 to 100) °C. It has a high tendency to warp, requiring good bed adhesion (e.g., with polypropylene sheets or glue stick). A heated chamber is recommended to reduce warping.

2.8. Polyether Ether Ketone (PEEK)

- *Properties*: Polyether Ether Ketone (PEEK) exhibits exceptional mechanical strength, with a tensile strength of approximately (90 to 100) MPa and a flexural modulus exceeding 3.6 GPa. It offers outstanding thermal stability, with a continuous service temperature of up to 250 °C and a glass transition temperature around 143 °C. PEEK is highly resistant to a wide range of chemicals, including acids, bases, and hydrocarbons, ensuring its durability in harsh environments. Its low wear rate and high fatigue resistance make it suitable for demanding applications. Additionally, PEEK is biocompatible, making it an ideal material for medical implants and surgical instruments [25].

- *Applications*: Polyether Ether Ketone (PEEK) is extensively used across various industries due to its outstanding mechanical properties, thermal stability, and chemical resistance. In the medical sector, PEEK is utilized for spinal implants, dental prosthetics, and orthopedic components due to its biocompatibility and radiolucency, allowing for clear imaging in medical scans. In aerospace, PEEK is employed in lightweight structural components, insulation panels, and high-performance fasteners, benefiting from its high strength-to-weight ratio and resistance to extreme temperatures. In the automotive industry, PEEK is used in fuel system components, bearings, and electrical connectors, where its resistance to wear and harsh chemicals enhances vehicle performance and longevity [9] [26] [27].
- *3D Printing Considerations*: PEEK requires a high extrusion temperature of 350 °C–400 °C and a heated bed around (120 to 160) °C. A heated chamber is essential to avoid warping, and the use of specialized high-temperature printers is necessary for optimal results [4].

2.9. Poly Cyclohexylenedimethylene Terephthalate Glycol-modified (PCTG)

Belonging to the same polyester family, combining the beneficial properties of traditional PETG, it provides enhanced impact strength, temperature resistance and stability, clarity, and ease of processing. It is a modified form of PET (Polyethylene Terephthalate) with added glycol. While specific studies on PCTG are limited, research on related materials and composite filaments provides valuable insights into its potential applications and characteristics.

PETG is one of the most commonly used filaments in FDM 3D printing due to its ease of printing and durability [28].

- *Applications* [29]:

1. Functional Prototypes & Mechanical Parts that require mechanical strength – Stronger than PLA, PETG is used for gears, brackets, and enclosures.

2. Medical Equipment & Protective Gear – Common for face shields, prosthetics, and medical device components due to its biocompatibility, chemical resistance and durability.

3. Food-Safe Containers – Certain PETG filaments, having clarity and safety, are FDA-approved, making them suitable for food storage and beverage packaging.

4. Outdoor Applications – Better UV resistance than PLA, making it ideal for signage, garden tools, and outdoor fixtures.

5. Durable and easy to work with for rapid manufacturing tools (aids and jigs).

- *3D Printing Considerations*: PCTG requires an extrusion temperature of (230 to 250) °C and a heated bed around (70 to 90) °C. It has low warping and good adhesion to common surfaces like PEI or glass. PCTG is relatively easy to print, offering good strength and clarity. It does not require a heated chamber [15].

2.10. Acrylonitrile Styrene Acrylate (ASA)

ASA is a thermoplastic polymer widely used in 3D printing, particularly valued for its superior weather resistance and mechanical properties. It shares similarities with Acrylonitrile Butadiene Styrene (ABS) but offers enhanced UV stability, making it ideal for outdoor applications [30] [31].

- *Applications*:

1. Automotive Industry. Prototyping and Functional Parts: ASA's durability and resistance to environmental factors make it ideal for creating prototypes and functional components such as bumper covers, side mirror housings, dashboard holders, and grilles.

2. Outdoor Signage and Fixtures. The filament's UV resistance ensures that outdoor signs maintain their color and structural integrity over time, even when exposed to direct sunlight. ASA is suitable for garden fixtures and other outdoor installations that require long-term durability and aesthetic stability.

3. Tooling. The material's strength and lightweight nature allow for the creation of sturdy, custom tools tailored to specific tasks, enhancing efficiency and ergonomics.

4. Electrical Enclosures: ASA's excellent weather and UV resistance make it suitable for manufacturing electrical enclosures (Protective Casings) that safeguard sensitive components in outdoor environments.

5. Sporting Goods: Equipment: The filament's impact resistance and ability to withstand various weather conditions make it ideal for producing durable sporting goods.

6. Architectural Models and Prototypes. ASA's durability and matte finish are beneficial for creating detailed architectural models and prototypes that require both aesthetic appeal and structural integrity.

- *3D Printing Considerations*: ASA requires an extrusion temperature of (240 to 260) °C and a heated bed around 90 °C–110 °C. It has low warping and needs a heated chamber to maintain optimal print quality. Due to fume emission during printing, adequate ventilation is recommended.

2.11. Polyvinyl Alcohol (PVA)

PVA is a synthetic polymer widely utilized in 3D printing, primarily as a support material due to its water-soluble nature. PVA dissolves readily in water, facilitating the removal of support structures from complex prints without the need for mechanical intervention. It is highly hygroscopic, and biodegradable. This can lead to issues such as bubbling and poor print quality. Therefore, it is crucial to store PVA filament in a dry, sealed container with desiccants to maintain its integrity [32].

- *Applications*:

1. Support Material. PVA is predominantly used as a support material in dual-extrusion 3D printing, especially for printing intricate designs with overhangs or internal cavities. Its compatibility with PLA makes it a preferred

choice for creating supports that can be easily dissolved in water, leaving a clean finish on the final print [33].

2. Prototyping. PVA facilitates the creation of complex prototypes by providing temporary support during the printing process, which can be removed effortlessly post-printing.

- *3D Printing Considerations*: PVA requires an extrusion temperature of (190 to 220) °C and a heated bed around (50 to 70) °C. PVA is prone to moisture absorption, so it should be stored in a dry environment. It prints well with PLA and other materials but may require careful handling to avoid degradation due to moisture.

2.12. High Impact Polystyrene (HIPS)

HIPS is a versatile thermoplastic renowned for its impact resistance, machinability, and cost-effectiveness. It is produced by blending polystyrene with polybutadiene rubber, enhancing its durability compared to general-purpose polystyrene [34].

- *Applications*:

1. Packaging. Due to its impact resistance and ease of processing, HIPS is widely used in packaging solutions. It is ideal for products subject to wear and tear.

2. 3D Printing. In 3D printing, HIPS serves both as a primary material and as a dissolvable support material, particularly with ABS prints.

3. Consumer Goods. Its durability and cost-effectiveness make it suitable for products like toys, household appliances, and office supplies.

4. Aerospace applications that withstand cryogenic thermal cyclin. [35].

- *3D Printing Considerations*: HIPS requires an extrusion temperature of (230 to 250) °C and a heated bed around (90 to 110) °C. HIPS has good adhesion to a variety of bed surfaces. It is easy to print and needs a heated chamber to prevent warping.

4. COMPARATIVE ANALYSIS OF HARD PLASTICS USED IN FDM

Fused Deposition Modeling (FDM) employs various thermoplastic materials, each offering distinct mechanical properties and suitability for different applications. Comparing various 3D printing materials is essential to select the appropriate filament for specific applications [4] [5] [6] [11] [16] [36] [37] [38] [39] [40] [41] [42] [43] [44] [45] [46] [47]. Table 1 presents a comparative analysis of some commonly used hard plastics in FDM. Based on it, the ranking of thermoplastics used in 3D printing is divided according to maximum tensile strength (Fig. 1), medium costs (Fig. 2) and heat resistance (Fig. 3).

Table 1

Main parameters defining hard plastics used in FDM

Property	Tensile Strength (MPa)	Heat Resistance (HDT)	Chemical Resistance	Cost (per kg)	Ease of 3D Printing	Dimensional stability
PLA	Moderate (50–70)	Low (~60 °C)	Low	Low ($15–40)	Very Easy	Good
Tough PLA	40–60	Low ~60	Low	$30–40	Easy	Good
PETG	45–55	Good (~80–85)	Moderate	$25–40	Easy	Excellent
PEI	Very High 85–110	Very High (~200 °C)	Excellent	High (ULTEM 225-340 $)	Very Difficult	Excellent
PC	High (55 – 75)	Moderate (~130-135 °C)	Moderate	Moderate ($30-93)	Difficult	Good
PP (Polypropylene)	30–40	~100–110	Very High	$40–80	Very Difficult	Poor
ABS	Moderate (30 – 45)	Moderate (~100-105 °C)	Low	Low ($20–50)	Moderate	Moderate
Nylon	Moderate (40–85)	Moderate (~70-120 °C)	High	Moderate ($50–73)	Moderate to Difficult	Poor (High Moisture Absorption)
CPE	40–55	~75–85	High	$35–60	Easy	Good
CPE+	50–70	~85–110	High	$40–70	Medium	Good
PEEK	Very High (90–100)	Very High (~300 °C)	Excellent	Very High ($300–500)	Extremely Difficult	Excellent
PCTG	High (50– 0)	Moderate (~80-100 °C)	Improved	Low ($20-60)	Easy	Good
PCTG CF	High (65–80)	High (~100-120 °C)	Improved	Moderate (approx. $50)	Moderate	Very Good (CF Reduces Shrinkage)
PET CF (Annealed)	75–90	~110–120	High	$50–80	Medium	Excellent
PCTG GF	High (60–75)	High (~100-120 °C)	Improved	Moderate (approx. 50 $)	Moderate	Very Good (GF Reduces Warping)
TPU 95A	20–30	~90–100	High	$35–60	Medium	Excellent
ASA	High (40–50)	Medium (~45)	Good	$20–48	High	Good
PVA	Low	Low (~30)	Good	$55–80	Moderate to Difficult	Moderate to less
HIPS	Medium	Medium (~40)	Good	$15–21	Easy	Good

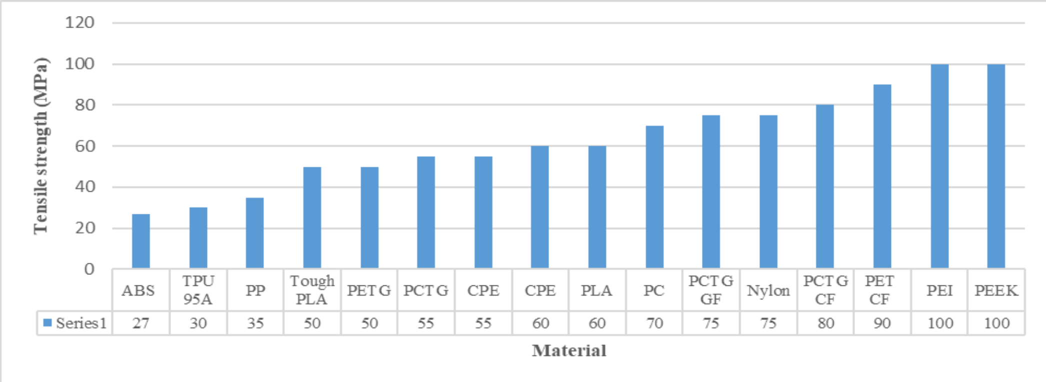

Fig. 1. Comparative diagram regarding the maximum tensile strength of thermoplastic materials used in FDM.

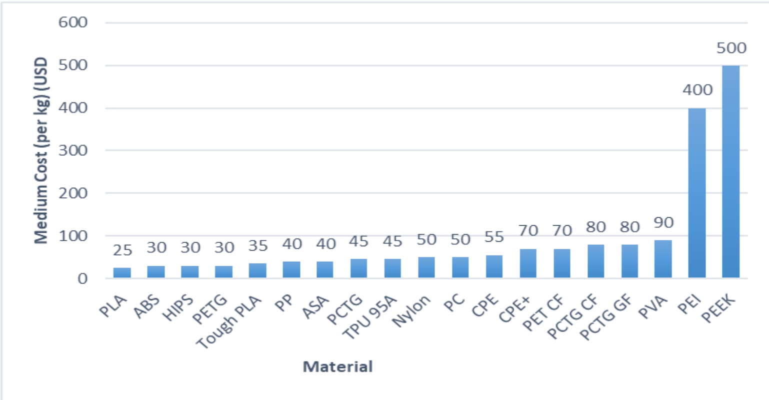

Fig. 2. Comparative diagram regarding medium costs of thermoplastic materials used in FDM.

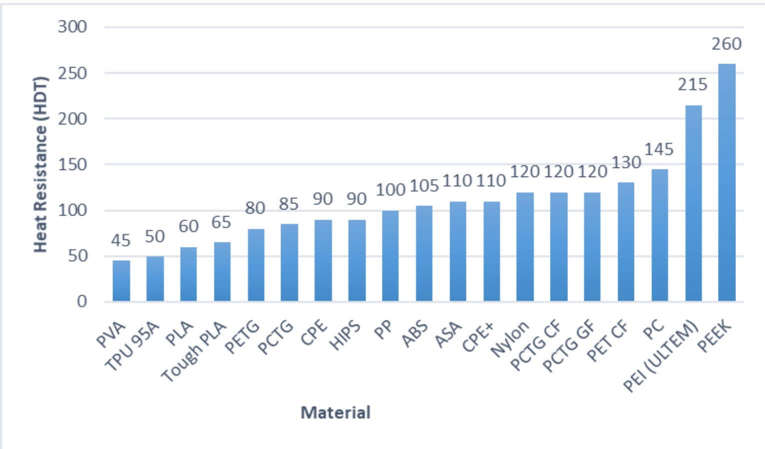

Fig. 3. Comparison chart of 3D printed thermoplastic materials in terms of heat resistance (HDT).

Specialized literature provides information resulting from research that leads to the grouping of the most used thermoplastic materials in 3D printing with molten filament deposition [48]. Groups of materials and application areas can be distinguished, as follows:

- Amorphous materials, characterized by low process shrinkage, low warping tendency, high dimensional stability, suitable for prototyping:
  - *Comodity* (low price) – ABS, SAN, HIPS;
  - *Egineering* (moderate temperature resistance, moderate strength stiffness) – ASA, PVA, PC;
  - *High performance* (high temperature resistance, high chemical resistance, high strength) – PAI, PPSU, PEEK, PEI;
- Semi-crystalline materials, characterized by high filament modulus, good intralayer adhesions, high part density and strength, suitable for load-bearing applications:
  - *Comodity* (low price) – PP;
  - *Egineering* (moderate temperature resistance, moderate strength stiffness) – PA6, PA12, TPE, PET, POM, PLA, TPU;
  - *High performance* (high temperature resistance, high chemical resistance, high strength) – PVDF, PEEK.

Table 2 gives a comparison of dimensional stability for the studied materials. Dimensional stability refers to the ability of material to maintain its shape and size under varying temperature and humidity conditions. The influencing factors that affect it are the coefficient of thermal expansion (CTE), moisture absorption, and thermal resistance [50] [51].

Some remarks can be made regarding the notions introduced by the comparative study of materials used in 3D printing.

- *Dimensional Stability* refers to the material's ability to maintain its dimensions after printing and under varying environmental conditions.
- *CTE* (*Coefficient of Thermal Expansion*) indicates how much a material expands or contracts with temperature changes. CTE measures how much a material expands or contracts when its temperature changes. It is expressed in ppm/°C (parts per million per degree Celsius), which tells you how much 1 meter of material will expand per degree Celsius increase in temperature. Lower values suggest better dimensional stability with temperature fluctuations. Figure 4 shows the ranking of thermoplastics in terms of the coefficient of thermal expansion.
- *Moisture Absorption* represents the percentage of water a material can absorb from the environment, which can affect mechanical properties and dimensional stability.

Table 2

Dimensional stability for the most used 3D printed materials

Material	Dimensional Stability	CTE (ppm / °C)	Moisture Absorption (%)
PLA	Good	~68–88	~0.5–1.0
Tough PLA	Good	~68–88	~0.5–1.0
PEI.	Excellent	~47	0.25
PC	Fair	~65–70	~0.15–0.3
PP	Poor	~100–150	~0.01–0.03
PETG	Excellent	~60–70	~0.13
ABS	Fair	~80–100	~0.2–0.4
Nylon	Poor	~114–175	~1.5–2.5
CPE	Good	~60–70	~0.13
CPE+	Good (improved vs. CPE)	~60–70	~0.13
PEEK	Excellent	~47	~0.5
PCTG	Good	~60	~0.2
PCTG CF	Very Good (CF Reduces Shrinkage)	~50	~0.15
PET CF (Annealed)	Excellent	~20–30	~0.1
PCTG GF	Very Good (GF Reduces Warping)	~55	~0.15
TPU 95A	Excellent	~100–150	~0.2–1.3
ASA	Good	~80–100	~1.0
PVA	Moderate to less	~50–100	~105.2
HIPS	Good	~90	~0.05–0.15

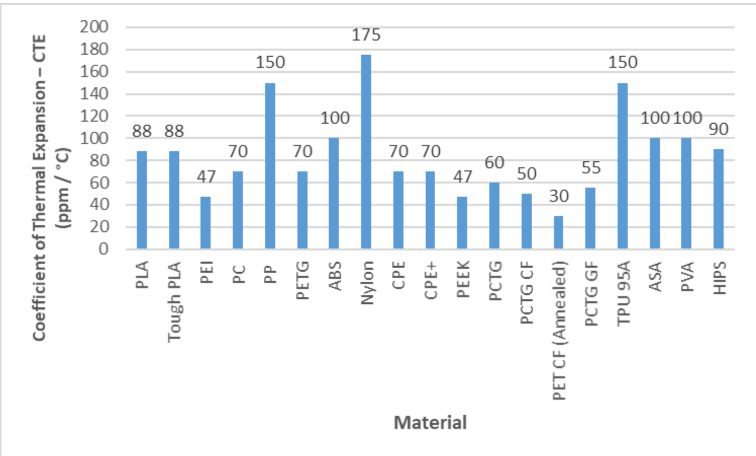

Fig. 4. 3D printed thermoplastic materials ranked by the maximum value of the coefficient of thermal expansion.

Some recommendations can be made regarding dimensional stability, as follows:

- *High Dimensional Stability*: Materials like PETG, PET CF, and TPU 95A exhibit excellent dimensional stability, making them suitable for precision applications.
- *Low CTE*: Materials with lower CTE values, such as PET CF, are less prone to dimensional changes with temperature variations.
- *Moisture Sensitivity*: Nylon has higher moisture absorption, which can lead to dimensional changes and affect mechanical properties. Proper storage and drying are essential for such materials. PVA undergoes changes to a milky or opaque appearance given by moisture absorption.

A comparison of the visual aspects of the studied 3D printed materials focusing on appearance, finish, and ease of achieving certain surface qualities in 3D printing is presented in Table 3.

The following comments can be made from the comparison based on gloss/finish, translucency, color availability and surface quality:

- *Gloss/Finish*: Materials such as PC, PCTG, and PEEK can have a glossy finish, with PC offering the clearest and most transparent appearance. ABS, PET CF, and PCTG CF/GF are usually matte, unless post-processed. PLA and PETG have a naturally smooth and semi-gloss finish, while Nylon and TPU 95A tend to have a more textured or fibrous appearance.
- *Translucency*: PC and PCTG are noted for their high translucency, making them suitable for parts where transparency is important. PETG and CPE also exhibit some level of translucency, especially in thin layers. Other materials such as PEI, ABS, Nylon, and reinforced composites (PCTG CF/GF, PET CF, PET CF Annealed) are usually opaque.
- *Color availability*: ABS and PCTG offer a wide range of colors, making them versatile for aesthetic and functional parts. PLA is also widely available in various colors, including specialty finishes (silk, metallic, glow-in-the-dark). PETG, CPE, and PC are available in standard colors but have fewer options than ABS or PLA. PEEK, PEI, and fiber-reinforced materials (PCTG CF, PCTG GF, PET CF) are more limited in color, often found in natural, black, or muted industrial tones. Nylon is commonly available in white or black but can be dyed post-printing. TPU 95A is usually available in neutral or muted colors but is flexible enough to be dyed.
- *Surface quality*: Materials such as PC, ABS, PETG, and PEEK tend to offer good surface finishes, with PC being one of the clearest and smoothest. PLA and PETG provide smooth, high-detail prints, but PETG may have minor stringing issues. Carbon fiber and fiberglass reinforcements (PCTG CF, PCTG GF, PET CF, and PET CF Annealed) introduce visible textures due to the embedded fibers, leading to a rougher, matte appearance. Nylon has a slightly rough, fibrous texture, while TPU 95A has a rubber-like matte finish with a soft feel.

Table 3

Visual aspects of the studied 3D printed materials

Material		Surface Quality	Color Availability	Translucency	Appearance
PLA	PLA has a slightly shiny finish	Smooth, glossy, visible layer lines, easy to post-process	Wide range (solid, metallic, silk, glow-in-the-dark, UV-reactive, color-changing)	Semi-transparent options available but not fully clear	Natural sheen, high color consistency, specialty textures available
Tough PLA	It retains many of PLA's good visual qualities	Smooth, slightly glossy, minimal layer lines	Wide variety of colors, including matte, metallic, and silk finishes	Mostly opaque, some semi-transparent options available	Professional, vibrant, and polished finish
PEI (Ultem 9085)	Matte to glossy (depending on post-processing)	Smooth, requires high extrusion temperature	Limited (usually yellow, amber, or translucent)	Low (typically opaque)	Solid, professional appearance
PC	Glossy, smooth	Excellent, can have a high-quality finish	Available in various colors, including clear	High (can be translucent)	Clear, transparent, glossy finish
PP	Its visual characteristics can vary depending on the printing process	Matte to slightly glossy, visible layer lines, smooth but not polished	Limited to neutral tones (white, black, gray, translucent)	Semi-translucent in thin layers, more opaque in thicker prints	Industrial, waxy or frosted, low detail compared to PLA or ABS
PCTG	Glossy, smooth finish	Can achieve very smooth and even surface quality	Wide range of colors, including transparent options	High (transparent options), great for light-diffusing applications	Shiny and clear appearance, with less visible layer lines
ABS	Matte to glossy (with post-processing like acetone vapor)	Moderate smoothness, may show layer lines	Available in a wide range of colors	Low (typically opaque)	Shiny if polished, matte if untreated
Nylon (PA6, PA12)	Matte	Smooth finish with some texturing depending on the extrusion temperature	White, black, and a range of colors	Low (opaque)	Often textured, with a slight sheen

Table 3. Continuation

CPE	Shiny surface. Vibrant appearance, suitable for aesthetic prints	Very smooth, glossy finish	Wide range – transparent, opaque, and vibrant colors. Minimal fading over time	Available in transparent and semi-transparent variants. Better resistance to fading	High-gloss and smooth. Good, fine details can be printed well
CPE+	More uniform slightly matte look, making it ideal for engineering applications.	Slightly smoother than CPE, with improved layer fusion	Fewer color options than CPE, mostly industrial colors	Less transparency, more opaque finishes	Slightly less glossy, but more uniform. Excellent, better layer bonding improves intricate details
PEEK	Matte, polished finish possible	Requires high-temperature printing for smooth surfaces	Limited color options (typically light amber or translucent)	Low (opaque)	Solid, durable look; glossy finish with post-processing
PCTG CF	Matte, slightly textured	Rougher than pure PCTG due to carbon fiber presence	Usually black or dark shades	Low (opaque)	Matte, with visible carbon fiber strands for texture
PET CF (Annealed)	Annealed PET CF prints typically exhibit a matte surface finish due to the presence of carbon fibers.	Proper drying of the filament before printing is crucial to prevent issues such as oozing, bubbling, and rough surfaces.	PET CF filaments are predominantly available in black, attributed to the carbon fiber content. Some manufacturers offer additional colors, such as blue and gray, with varying densities.	Opaque, translucency being eliminated due to carbon fibers.	Matte, textured appearance due to the carbon fibers.
PCTG GF	Matte, textured	Rougher surface due to glass fibers	Generally available in natural or grayish tones	Low (opaque)	Matte, with visible glass fiber reinforcement texture
TPU 95A	Translucency can vary based on the manufacturer and specific product formulation.	Smooth surface finish and high reliability, suitable for applications requiring both flexibility and a refined appearance	Multiple colors. For example, white, black, red, and blue, with possibility of additional options.	Some TPU 95A filaments may have a translucent quality, allowing light to pass through to some extent, while others are more opaque	The overall appearance of TPU 95A prints is influenced by printing parameters and post-processing techniques
ASA	High-quality surface finishe	Smooth, opaque and glossy finish. Optimal surface quality depends on extrusion and bed temperatures an control if printing environment.	Variety of colors, including standard options like black, white, and grey, as well as vibrant hues such as red, blue, and green.	ASA is inherently an opaque material, resulting in prints that are not translucent.	Smooth surface and uniform color
PVA	Translucent white	Smooth and clean surface finish	Natural form being typically white or translucent.	Translucent appearance with alteration to milky or opaque given by moisture absorption	Translucent white appearance. Over time, it could become more opaque
HIPS	Matte surface finish	High-quality, smooth, matte surface finish that is pleasant to the touch	Wide range of colors, including white, black, gray, and various shades of blue, red, and green	In natural form it exhibits a white, translucent color	Consistent, scratch-resistant, matte finish

The ease of printing for 3D printed materials can be analyzed based on temperature, deformation, adhesion, and printer compatibility requirements (Table 4).

Regarding the levels of easy of printing, they can be detailed as follows [15]:

- *Easiest to Print*: PCTG is the most user-friendly, offering low warping, good adhesion, and no special requirements.
- *Moderate Difficulty*: ABS, Nylon, PCTG CF, and PCTG GF need careful bed adhesion management and possibly an enclosed chamber (ABS, Nylon).
- *Difficult to Print*: PC and PEI need high temperatures and enclosure to reduce warping.
- *Extremely Difficult*: PEEK requires an industrial 3D printer due to its very high extrusion and bed temperatures.

Table 5 summarizes the Shore D hardness values for various 3D printing materials [49].

The *Shore hardness scale* measures the resistance of a material to indentation. The *Shore D scale* is typically used for harder plastics, while the *Shore A scale* is used for softer, more flexible materials. For instance, TPU 95A is primarily measured on the Shore A scale, where it has a hardness of 95A, which corresponds to approximately 48 on the Shore D scale.

The provided values are typical for these materials, but actual hardness can vary based on specific formulations, processing conditions, and manufacturer specifications.

Figure 5 give an image of the hierarchy of the thermoplastic materials in terms of easy of printing introducing scores from low to extremely high accompanied by some specific characteristics.

Table 4

Easy of printing based on a set of parameters

Material	Ease of Printing	Extrusion Temp (°C)	Bed Temp (°C)	Warping Tendency	Adhesion Requirement	Special Printer Requirements
PLA	Very Easy	190–220	20–60°	Low	Good; glass, PEI sheets, and painter's tape	Cooling fan recommended
PEI (Ultem 9085)	Very Difficult	350–390	120–160	High	PEI sheet, adhesives	High-temp, enclosed chamber
PC	Difficult	260–310	90–110	High	Glue, PEI bed recommended	Enclosed chamber recommended
PP	Hard prone to warping, poor adhesion	220–250	100–120	Very High	Poor adhesion to most surfaces, requiring PP tape, glue stick or Magigoo PP adhesive	Heated bed, enclosed chamber (recommended)
ABS	Moderate	220–250	90–110	High	Glue, ABS slurry	Enclosed chamber helps
Nylon (PA6, PA12)	Moderate to Difficult	240–270	60–80	High (absorbs moisture)	Glue stick, textured bed	Dry storage needed
CPE	Easy	230-270	70–90	Moderate	Good	No enclosure needed
CPF+	Easy	250–275	80–100	Lower than CPE	Improved, less prone to warping	Enclosure recommended for larger prints
PEEK	Extremely Difficult	360–400	120–160	Very High	PEI sheet, high-temp bed	Industrial-grade printer required
PCTG	Easy	240–260	70–80	Low	Minimal (sticks well)	Works with standard FDM printers
PCTG CF	Moderate	250–270	70–80	Low	Good, may need textured bed	Hardened nozzle recommended
PCTG GF	Moderate	250–270	70–80	Low	Good, may need textured bed	Hardened nozzle recommended
ASA	Moderate to Difficult	220–250	90–110	High	A brim or raft can enhance bed adhesion, minimizing warping	Adequate ventilation to control smoke emissions during printing
PVA	Moderate to Difficult	185–200	45–60°	Low	Utilize surfaces such as PEI sheets or painter's tape to enhance adhesion	Dual extruder capabilities. Filament requires drying at 80 °C for 8–12. It needs cooling fans.
HIPS	Easy	220–270	90–115	High	Needs surfaces like PEI sheets or glass beds treated with adhesives (e.g., glue sticks or hairspray) to enhance adhesion	Enclosed printing environment, proper ventilation to manage emissions

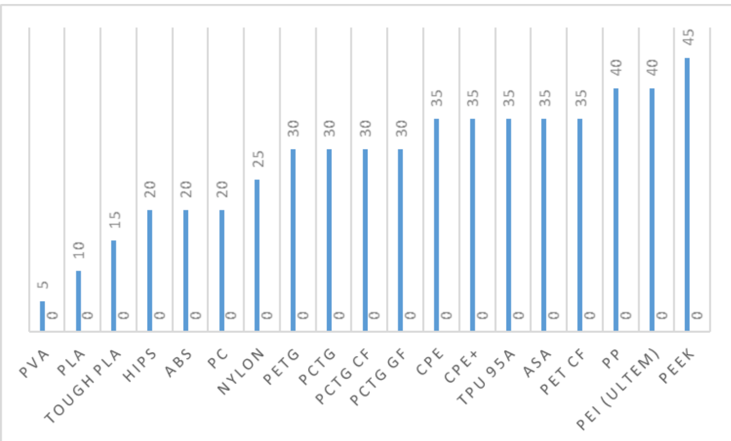

Fig. 5. Easy of printing of printed 3D thermoplastics, considering the score assigned: 5 – very low, 10 – low (weak to solvents, acids, and bases); 15 – (slightly improved over PLA); 20 – moderate (soluble in limonene); 20 – (weak to acetone, alcohols, and some solvents); 25 – moderate to good (resistant to many solvents, but absorbs moisture); 30 – good (resistant to acids, alcohols, and oils); 30 – good (better than PETG, resistant to chemicals and impact); 30 – good (carbon fiber enhances stability); 30 – good (glass fiber enhances stability); 35 – high (resistant to many chemicals); 35 – high ((improved over CPE, more stable); 35 – high (resistant to oils, greases, and many solvents); 35– high (better than ABS, resistant to UV and chemicals); 35 – high (enhanced with carbon fiber for stability); 40 – very high (excellent resistance to most chemicals); 40 – very high (used in aerospace and medical applications); 45 – extremely high (one of the most chemically resistant 3D printing materials).

Table 5

Hardness of plastic materials used in FSM

Material	Shore D Hardness	Notes
PLA	60–80	Commonly used for general-purpose 3D printing.
Tough PLA	75–80	Offers increased toughness compared to standard PLA.
PETG	70–80	Balances strength and flexibility, suitable for functional parts.
ABS	70–80	Known for its durability and impact resistance.
PET CF	80–85	Carbon fiber reinforcement enhances stiffness. It is harder than PETG, PLA, and ABS, close to ASA.
PET CF (annealed)	80–85	Annealing can increase hardness; specific values depend on processing conditions. PET CF is stiff and resistant to surface indentation.
Nylon	60–75	Offers good mechanical properties and wear resistance.
CPE	76	Provides chemical resistance and dimensional stability.
CPE+	77	Enhanced version of CPE with improved temperature resistance.
PC	81	High strength and heat resistance, suitable for demanding applications.
PP	42	Lower hardness, offering flexibility and chemical resistance.
TPU 95A	4880 C/ 94 A	Flexible material measured on the Shore D scale; equivalent to 95A on the Shore A scale.
ASA	75–80	Slightly softer than ABS but tougher than PLA
PVA	30–50	Much softer than PLA or ABS, slightly harder than silicone. PVA is flexible and rubbery rather than rigid.
HIPS	65–75	Softer than ABS and ASA but tougher than PLA. HIPS is semi-rigid but impact-resistant.

A review of the late researched bibliographic sources are presented in Table 6 grouped by common topics subdivided into specific topics. Among the possible topics, one can find mechanical properties, process parameters, applications, and reviews. Some recent articles in the field of 3D printed thermoplastics applications are described and critically analyzed in more detail, being grouped in specific topics, such as Tribological applications, 3D-Printed Gears, Aerospace Applications, Automotive Applications, Molds and Dies, and Multi-Materials. A section of common subjects is represented by the Review/overview articles, being described specific topics from the point of view of application fields, such as 3D printing of polymers, Industry 4.0, Industry 4.0 and 3D Printing, Industry 5.0 Innovations, Limitations of 3D printing, technologies.

Table 6

Grouping major reference sources based on common and specific topics

Common subject	Specific subject	Title	Authors / Year	Short description
Mechanical Properties	Mechanical Properties	Finite element analysis of thermoplastic polymer extrusion 3D printed material for mechanical property prediction [10]	Bhandari & Lopez-Anido / 2018	Uses FEA for predicting mechanical properties of extruded thermoplastics.
	High-Performance Polymer Blends	High-Performance Polymer Blends: Manufacturing of Polyetherimide (PEI)–Polycarbonate (PC)-Based Filaments for 3D Printing [16]	Singh & Hubert / 2024	Evaluates mechanical and thermal properties of PEI-polycarbonate blends.
	Mechanical Properties of PEI Parts	Mechanical properties analysis of polyetherimide parts fabricated by fused deposition modeling [5]	Jiang, S. et al. / 2019	The entire process of polyetherimide (PEI) 3D printing from filament extrusion to printing is studied. The filament orientation and nozzle temperature were closely related to the mechanical properties of printed samples.
	Medical Applications of PEI & PEEK	Polyether ether Ketone (PEEK) and Polyetherimide (PEI) blends for 3D printed medical devices [9]	McCrickard et al. / 2024	Examines mechanical performance of PEEK/PEI for biocompatible medical devices.
	Mechanical Strength Enhancements	Enhancing Mechanical Properties of Polymer 3D-Printed Parts [22]	Amza, C. G. et al. / 2021	Focuses on tensile and impact strength improvements in AM polymers.
	Mechanical Design	A novel tape spring hinge mechanism for quasi-static deployment of a satellite deployable using shape memory alloy [52]	Jeong, J. W. et al. / 2014	Introduces a novel hinge mechanism, relevant for flexible printed parts.
	Mechanical Properties	Mechanical properties of ULTEM 9085 material processed by fused deposition modeling [36]	Byberg, K.I. et al. / 2018	Examines tensile, flexural, and impact properties of Ultem 9085, showing significant anisotropy due to build orientation.
	Build Orientation Influence	Influence of orientation on mechanical properties for high-performance fused filament fabricated Ultem 9085 and electro-statically dissipative polyetherketoneketone [40]	Kaplun, B.W. et al. / 2020	Analyzes how build orientation affects tensile and compression properties of Ultem 9085 and PEKK.
	Mechanical & Thermal Properties	Mechanical and thermal behavior of Ultem® 9085 fabricated by fused-deposition modeling [41]	Padovan, E. et al. /2020	Investigates both mechanical and thermal stability of Ultem 9085, confirming its high-temperature resistance.

Table 6. Continuation

	Material Characterization	Material characterization of a high performance additive manufacturing material for efficient component design [42]	Rehman, F.; Diston, J. / 2020	Studies tensile, flexural, and impact properties of Ultem 9085 for structural applications.
Process Parameters	Research on 3D-printed PEEK and PEI components	An overview on the influence of process parameters through the characteristic of 3D-printed PEEK and PEI parts [4]	A. El Magri, et al. / 2021	Reviews the influence of process parameters on 3D-printed PEEK and PEI components. Experimental graphs illustrate the impact of print temperature, build orientation, and cooling rates on mechanical performance.
	Manufacturing of fiber-reinforced polymer composites (FRPCs)	Additive manufacturing (3D printing) technologies for fiber-reinforced polymer composite materials: A review on fabrication methods and process parameters [53]	Ramesh, M. et al. / 2024	This review focuses on the manufacturing of fiber-reinforced polymer composites (FRPCs) in relation to process parameters and properties of the polymer composites.
	Extrusion Additive Manufacturing (EAM) applied to PEI	Extrusion additive manufacturing of PEI pellets [6]	Fabrizio, M., et al. / 2022	The article studies PEI 1000, which offers outstanding mechanical and thermal properties, used for producing Extrusion Additive Manufacturing (EAM) functional components.
	Influence on main FFT parameters on PEEK	Optimization of printing parameters for improvement of mechanical and thermal performances of 3D printed poly (ether ether ketone) parts [54]	El Magri,A. et al. / 2020	Design of experiments analysis performed on the main FFF parameters of PEEK - temperature, printing speed, raster orientation, and layer thicknesses.
	Influence on main FDM parameters on PEI	Investigating effects of fused-deposition modeling (FDM) processing parameters on flexural properties of ULTEM 9085 using designed experiment [36]	Gebisa, A. W., & Lemu, H. G. / 2018	The investigation is carried out on ULTEM 9085 material, regarding five parameters: air gap, raster width, raster angle, contour number, and contour width.
	Influence on main FDM parameters on PEEK	Additive layer manufacturing of poly (ether ether ketone) via FDM [55]	Rinaldi, M. et al. /2018	This paper concerns the FDM process of PEEK, analysing the results of mechanical (tensile tests), thermal (DSC), microstructural (XRD) and morphological (OM and CT-scans) testing of samples.
	Influence on main FDM parameters on PEEK reinforced with carbon nanotubes	Fused Deposition Modelling of high temperature polymers: Exploring CNT PEEK composite [56]	Berretta, S. et al. / 2017	The article presents the study of PEEK produced with 1% and 5% carbon nanotubes (CNTs) and processed in a modified FDM system operating with high temperature. The tensile strength, layer bonding and microstructure of the plain and CNT loaded PEEK samples were investigated.
	Nozzle temperature and building orientation	Effects of nozzle temperature and building orientation on mechanical properties and microstructure of PEEK and PEI printed by 3D-FDM [57]	Ding, S. et al. / 2019	PEEK and PEI were 3D printed to investigate the relationship of nozzle temperature, building orientation and material properties by analyzing the morphology, chemical composition and SEM.
	PEI 3D printing parameters	Mechanical properties analysis of polyetherimide parts fabricated by fused deposition modeling [5]	Jiang, S. et al. / 2019	The entire process of PEI 3D printing from filament extrusion to printing is studied. The filament orientation and nozzle temperature were closely related to the mechanical properties of printed samples.
	Orientations with several solid and sparse configurations.	Role of infill parameters on the mechanical performance and weight reduction of PEI Ultem processed by FFF [58]	Forés-Garriga, A. et al. / 2020	Investigation of the role of infill parameters on the mechanical performance and weight reduction of ULTEMTM 9085 samples processed by FFF, under tensile, flexural, and shear loading conditions in six different orientations with several solid and sparse configurations.
Applications	Tribological applications	Polymer composites for tribological applications [59]	Friedrich, K. / 2018	Special design principles of polymer composites for low friction and wear under sliding against smooth metallic counterparts, and modern additive manufacturing methods for friction and wear loaded polymer parts.
		Tribological Aspects of Additive Manufacturing [60]	Tyagi, R. et al.	A comprehensive resource that delves into the intersection of additive manufacturing (AM) and tribology
		Tribological behavior of PEEK based composites with alternating layered structure fabricated via fused deposition modeling [61]	Lv, X. et al. / 2024	Novel PEEK-based composites using multi-material (FDM) consisting of alternating layers of short carbon fiber-reinforced PEEK and silicon dioxide-filled PEEK. The contact pressure significantly influences tribological performance, with lower friction and wear occurring at higher contact pressures.
		Investigation of Tribological Behavior and Failure Mechanisms of PEEK-Based Composites, Babbitt Alloy, and CuSn10Pb10 Bimetal for Wind Turbine Main Shaft Sliding Bearings Under Simulated Operational Conditions [62]	Liu, W. et al. / 2025	This study investigates the tribological behavior and failure mechanisms of several sliding bearing materials under complex operational conditions. Multi-condition friction and wear tests were conducted to evaluate the friction coefficient, friction temperature rise, and volume wear rate of Babbitt alloy (ZChSnSb11-6), bimetal CuSn10Pb10, pure PEEK, and the 10% PTFE-filled modified PEEK composites.
		Determination of "tribological performance working fields" for pure PEEK and PEEK composites under dry sliding condition [63]	Maslavi, A. et al. / 2024	In this study, the influence of sliding velocity and applied load values on the friction and wear behavior of pure PEEK, 30 wt% glass fiber reinforced PEEK (PEEK-30GF), 30 wt% carbon fiber reinforced PEEK (PEEK-30CF) and 10 wt% carbon fiber+10 wt%graphite +10 wt%poly-tetra-fluoro-ethylene (PTFE) filled PEEK (ie. High (H) pressure (P) and velocity (V) resistant PEEK (PEEK-HPV)) composites rubbing against AISI 304 stainless steel disc was investigated.
		Tribological studies of 3D printed ABS and PLA plastic parts [64]	Roy, R., & Mukhopad-hyay, A. / 2021	The study revealed that PLA exhibited higher friction coefficients compared to ABS while ABS samples showed greater wear resistance than PLA.
		Tribological properties of 3D printed polymers: PCL, ABS, PLA and Co polyester [65]	Ramadan, M.A. et al. / 2023	Investigates the wear and friction characteristics of four commonly used 3D-printed polymers: Polycaprolactone (PCL), Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), and Co-Polyester.
		Tribological properties of 3D printed polymer composites-based friction materials [66]	Gbadeyan, O. J.et al. / 2021	A comprehensive review of advancements in the tribological performance of 3D-printed polymer nanocomposites.
		Tribological properties improvement of 3D-printed parts by in-process addition of graphite particles into the top layer [67]	Sukri, I. A. A. et al. / 2023	Investigates enhancing the wear and friction characteristics of 3D-printed PLA components by incorporating of graphite particles during the printing process

Table 6. Continuation

Applications	3D-Printed Gears / Review on 3D printed spur gears	Wear Analysis of 3D-Printed Spur and Herringbone Gears Used in Automated Retail Kiosks Based on Computer Vision and Statistical Methods [68]	Bryła, J. et al. / 2023	Analysis how 3D-printed gears are a reliable choice for long-term exploitation in mechanical systems by applying (1) vision-based inspection of the gears' cross-sectional geometry and (2) statistical characterization of the selected kinematic parameters and torques generated by drives.
		Comparative study about dimensional accuracy and form errors of FFF printed spur gears using PLA and Nylo [69]	Buj-Corral, I. et al. / 2023	Comparison of dimensional accuracy and form errors of FFF 3D printed spur gears of PLA and Nylon-PA6
		An analysis of polymer gear wear in a spur gear train made using FDM and FFF methods based on tooth surface topography assessmen [37]	Pisula, J. et al. / 2021	Analysis of gears made of ABS M-30, ULTEM 9085 (PEI) and PEEK in terms of economical application and strength parameters.
		Surface durability of 3D-printed polymer gears [70]	Ciobanu R. et al. / 2024	Experimental determinations carried out regarding the ability of 3D-printed gears to be integrated into mechanisms without lubrication.
		Recent advancements in 3D printing for gear design and analysis: A comprehensive review [71]	Pujari, L. et al. / 2024	Review paper on 3D printed spur gears, with focus on their design, material selection, manufacturing processes, and assessment of contact strength.
		Wear characteristics of 3D-printed spur gears: material type and design parameters effects [72]	Doğan, O., & Kamer, M. S. / 2025	Wear characteristics of polymer gears produced by AM, mainly focusing on asymmetric gears that present unique challenges in conventional machining.
		Accelerated testing of the Wear Behavior of 3D-printed Spur Gears [73]	Portoaca A.I. et al. / 2024	Research demonstrates that ABS gears exhibit superior wear resistance compared to their PLA counterparts. Additionally, annealing PLA results in a modest improvement in durability.
	Aerospace Applications	Structural integrity of the aircraft interior spare parts produced by additive manufacturing [74]	Kobenko, S. et al. / 2022	Evaluates the suitability of Ultem 9085 for aircraft interior parts using mechanical testing and CT scanning.
		Mechanical performance analysis of Ultem 9085 in a heated, irradiated environment [39]	Ng, M.B.; Brennan, S.N. / 2018	Evaluates the mechanical performance of Ultem 9085 in high-temperature and radiation conditions, relevant for aerospace applications and others related.
	Automotive Applications	AFM Analysis of 3D Printing PEI for Automotive Applications [2]	Nguyen, K. Q. et al. / 2023	Atomic Force Microscopy used to analyze the surface quality and roughness of 3D-printed PEI components for automotive use with focus on the microstructural characteristics.
	Molds and Dies	Manufacturing and performance of 3D printed plastic tools for air bending applications [38]	Zaragoza, V.G., et al. / 2021	Study concludes that with appropriate material selection and printing parameters, 3D-printed polymeric tools made of PC compared to those of PLA can effectively perform in air bending applications.
		The Use of Additive Manufacturing Techniques in the Development of Polymeric Molds: A Review [75]	Pelin, G. et al. / 2024	3D printing as solution that can help production of molds and dies more efficiently, in terms of design complexity and flexibility, timeframe, costs, and material consumption reduction as well as functionality and quality enhancements.
	Tools for sheet metal cutting	Investigation of FDM-Based 3D Printing for Optimized Tooling in Automotive and Electronics Sheet Metal Cutting [76]	Szalai, S. et al. / 2025	Assessment of the feasibility and performance of FDM-printed tools in sheet metal cutting operations, aiming to provide cost-effective and efficient alternatives to traditional tooling methods.
	Multi-Material	Multi-material additive manufacturing of high temperature polyetherimide (PEI)–based polymer systems for lightweight aerospace applications [77]	Vakharia, V. S. et al. / 2023	Explores the use of fused filament fabrication (FFF) to create multi-material composites using ULTEM (a PEI-based polymer) and carbon-fiber-infused ULTEM.
		Concurrent multi-material and multi-scale design optimization of fiber-reinforced composite material and structures for minimum structural compliance [21]	Duan Z. et al. / 2023	Methodology for a Multi-scale and Multi-material Composite Anisotropic Penalization (MMCAP) model to investigate design optimization of a fiber-reinforced variable stiffness (VS) composite structure to minimize structural compliance.
Reviews / Overviews	3D printing of polymers	State-of-the-art review on fused deposition modeling (FDM) for 3D printing of polymer blends and composites: Innovations, challenges, and applications [78]	S. Ali, et al. / 2024	The review underscores FDM's significant contributions to diverse industries by providing sustainable and customizable manufacturing solutions.
	Industry 4.0	Printing the Future Layer by Layer: A Comprehensive Exploration of Additive Manufacturing in the Era of Industry 4.0 [79]	Bănică, M. et al. / 2024	Reviews AM's role in Industry 4.0.
	Industry 4.0 and 3D Printing	3D printing in materials manufacturing industry: A realm of Industry 4.0 [80]	Tamir, T. S. et al. / 2023	Reviews AM's integration in digital and smart manufacturing.
	Industry 5.0 Innovations	Changes and improvements in Industry 5.0: A strategic approach to overcome the challenges of Industry 4.0 [81]	Khan, M. et al. / 2023	Analyzes AI-human collaboration and sustainable practices in AM.
	Limitations of 3D Printing	Advancements and limitations in 3D printing materials and technologies: a critical review [82]	Iftekar, S. F. et al. / 2023	Discusses material innovations and technological barriers in AM.
	Technologies	Manufacturing technologies of polymer composites – a review [7]	Wu, C. et al. / 2023	A comprehensive review of manufacturing technologies for polymer composites, summarizing recent advancements in polymer processing, including additive manufacturing.

5. REVIEWS AND OVERVIEWS ARTICLES

In their comprehensive review [78], Deiab, and Pervaiz delve into the multifaceted applications of Fused Deposition Modeling (FDM) within the context of Industry 4.0, highlighting its pivotal role in various sectors:

1. *Engineering Products*: FDM is instrumental in the rapid prototyping and production of complex engineering components. Its ability to fabricate intricate geometries with high precision makes it invaluable for developing customized parts in automotive and aerospace industries. This adaptability not only accelerates the design process but also reduces production costs and time-to-market.
2. *Agricultural Tools*: The agricultural sector benefits from FDM through the creation of tailored tools and equipment. Farmers can design and produce specific implements that cater to unique farming needs, enhancing efficiency and productivity. This on-demand manufacturing capability allows for quick adjustments and innovations in farming practices.
3. *Biomedical Implants*: FDM's precision and customization are particularly advantageous in the medical field. It enables the production of patient-

specific implants and prosthetics, ensuring better fit and comfort. The technology supports the fabrication of complex structures, such as scaffolds for tissue engineering, which are essential for advanced medical treatments.

4. *Packaging Industry*: In packaging, FDM offers the flexibility to create customized packaging solutions that meet specific requirements. This includes producing prototypes for testing and validation, as well as manufacturing small batches of specialized packaging designs. The ability to quickly iterate and modify designs leads to more efficient and effective packaging solutions.

The authors also address the challenges associated with FDM, particularly concerning the mechanical performance of 3D-printed parts made from polylactic acid (PLA) and its blends. They note that while FDM offers numerous advantages, the mechanical properties of PLA-based components often do not match those of conventionally manufactured parts. To mitigate this, the review explores material modifications and advanced additive manufacturing techniques aimed at enhancing the functionality, mechanical properties, and environmental adaptability of complex geometries produced via FDM.

Bănică et al., in the review [79], delve into the transformative impact of Additive Manufacturing (AM) within the Industry 4.0 paradigm, highlighting its diverse applications across multiple sectors:

1. *Aeronautics*: AM has revolutionized the aeronautics industry by enabling the production of lightweight, complex components that were previously unachievable with traditional manufacturing methods. This advancement has led to significant improvements in fuel efficiency and performance. The ability to produce parts with intricate geometries reduces material waste and allows for rapid prototyping, accelerating the development of innovative aerospace technologies.
2. *Automotive Industry*: In the automotive sector, AM facilitates the rapid prototyping of parts, allowing for swift design iterations and customization. This capability accelerates the development process and enables manufacturers to tailor vehicles to specific customer preferences. Additionally, AM supports the production of complex components that enhance vehicle performance and reduce overall weight, contributing to improved fuel efficiency and reduced emissions.
3. *Biomedicine*: The medical field benefits immensely from AM through the creation of patient-specific implants and prosthetics. This customization ensures a better fit and improved functionality for patients. Moreover, AM enables the fabrication of complex structures, such as scaffolds for tissue engineering, which are essential for advanced medical treatments and research. The precision and adaptability of AM technologies have opened new avenues in personalized medicine and complex surgical procedures.

The authors also discuss various AM processes, including binder jetting, direct energy deposition, and powder bed fusion, each offering unique advantages depending on the application. Materials utilized in AM span metals, polymers, ceramics, and composites, broadening the scope of potential applications. Innovations such as high-speed sintering, continuous liquid interface production, and bioprinting are highlighted as ongoing advancements pushing the boundaries of what AM can achieve.

Looking ahead, the review addresses the future prospects of 4D and 5D printing technologies. These emerging fields involve creating structures that can change over time or have enhanced mechanical properties, respectively, opening new possibilities in adaptive and resilient design. The integration of these technologies is poised to revolutionize further manufacturing processes, making them more efficient and adaptable to changing demands.

In a comprehensive study [80], Tamir et al. explore the transformative role of 3D printing within the materials manufacturing industry, positioning it as a cornerstone of Industry 4.0. The authors highlight several key applications and benefits of integrating 3D printing technologies:

1. *Rapid Prototyping and Design Flexibility*: 3D printing enables the swift creation of prototypes, allowing for accelerated design iterations and reduced time-to-market for new products. This flexibility facilitates innovation and customization, meeting diverse consumer demands.
2. *Production of Complex Geometries:* The technology allows for the fabrication of intricate structures that are challenging or impossible to achieve with traditional manufacturing methods. This capability is particularly advantageous in industries requiring complex component designs.
3. *Material Efficiency and Waste Reduction*: By building objects layer by layer, 3D printing minimizes material waste, promoting sustainable manufacturing practices. This efficiency not only conserves resources but also reduces production costs.
4. *Supply Chain Optimization*: The adoption of 3D printing can lead to decentralized production models, reducing the need for extensive inventory and enabling on-demand manufacturing. This shift enhances supply chain resilience and responsiveness.

The authors also discuss the integration of 3D printing with other Industry 4.0 technologies, such as artificial intelligence and the Internet of Things, to create smart manufacturing systems. These systems are capable of self-monitoring and optimization, leading to improved product quality and operational efficiency.

Khan et al., in article [81], explore the evolution from Industry 4.0 to Industry 5.0, emphasizing the strategic enhancements necessary to address the challenges posed by the former. A pivotal aspect of this transition is the integration of Additive Manufacturing (AM) technologies, which play a crucial role in realizing the human-centric and sustainable objectives of Industry 5.0.

1. *Human-Centric Manufacturing*: Industry 5.0 shifts focus towards collaborative interactions between humans and machines. AM facilitates this by enabling the creation of customized tools and interfaces tailored to individual worker needs, thereby

enhancing ergonomics and safety. This personalization ensures that technology adapts to humans, promoting a more inclusive work environment.

2. *Sustainable Production*: The authors highlight the environmental benefits of AM, particularly its potential to reduce material waste through precise layer-by-layer fabrication. This efficiency aligns with the sustainability goals of Industry 5.0, promoting resource conservation and minimizing the ecological footprint of manufacturing activities.
3. *Resilient Supply Chains*: AM contributes to supply chain resilience by enabling decentralized and on-demand production. This flexibility allows manufacturers to respond swiftly to disruptions, reducing dependency on centralized production facilities and enhancing the ability to meet dynamic market demands.

The article also addresses the integration of AM with emerging technologies such as artificial intelligence and the Internet of Things. This convergence leads to the development of intelligent manufacturing systems capable of self-optimization and real-time responsiveness, further advancing the principles of Industry 5.0.

Iftekar et al. [82], in the critical review, explore the advancements and limitations of 3D printing materials and technologies, focusing on their applications across various industries. The authors highlight the transformative impact of 3D printing in enabling the production of complex designs and shapes, which has led to an exponential increase in its applications. However, they also address significant challenges, including high costs, low printing speeds, limited part sizes, and strength. The review emphasizes the need for continued research and development to overcome these limitations and fully realize the potential of 3D printing technologies in manufacturing.

Some advancements are discussed as follows:

- *Material Development*: The introduction of new materials has significantly expanded the applications of 3D printing. Innovations in polymers, metals, ceramics, and composite materials have enabled the production of components with enhanced mechanical properties, thermal stability, and biocompatibility, catering to diverse industrial needs.
- *Technological Innovations*: Advancements in 3D printing technologies, such as multi-material printing and improvements in additive manufacturing processes, have facilitated the creation of complex geometries and structures that were previously unattainable. These innovations have streamlined production workflows and reduced the time from design to final product.

Among the critically analyzed limitations, the following can be highlighted:

- *High Costs*: Despite technological progress, the costs associated with 3D printing remain a significant barrier. Expenses related to equipment acquisition, material procurement, and post-processing can be prohibitive, especially for small and medium-sized enterprises.
- *Printing Speed*: Current 3D printing processes often involve prolonged build times, making them less competitive for mass production compared to traditional manufacturing methods. Enhancing printing speeds without compromising quality is an ongoing challenge.
- *Size Constraints*: The build volume of many 3D printers limits the size of producible parts. While large-scale 3D printers exist, they are often costly and less accessible, restricting the technology's applicability for producing sizable components.
- *Material Strength*: Some 3D-printed materials exhibit inferior mechanical properties compared to their conventionally manufactured counterparts. Issues such as anisotropy, where material properties differ based on orientation, can affect the performance and reliability of printed parts.

In the comprehensive review [7], Wu et al. delve into the manufacturing technologies of polymer composites, emphasizing their extensive applications across various industries. The authors categorize polymer composites based on their matrices—thermoplastic and thermosetting—and discuss their respective properties and applications.

1. *Thermoplastic Polymer Composites*: These composites are known for their recyclability and formability upon heating. They are extensively utilized in aerospace and automotive industries due to their excellent mechanical properties and ease of processing. The ability to reshape thermoplastic composites makes them ideal for applications requiring complex geometries and lightweight structures.
2. *Thermosetting Polymer Composites*: Characterized by their heat resistance and structural integrity, thermosetting composites are widely used in applications where durability and thermal stability are crucial. Once cured, these materials do not melt upon reheating, making them suitable for high-temperature environments.

The review highlights several manufacturing techniques employed to enhance the performance and longevity of polymer composites:

- *Surface Coating*: Applying protective layers to composites to improve properties such as corrosion resistance, wear resistance, and overall durability.
- *Additive Manufacturing* (3D Printing): Utilizing layer-by-layer fabrication methods to create complex composite structures with tailored properties, enabling rapid prototyping and customization.
- *Magnetic Pulse Powder Compaction*: A technique that uses magnetic pulses to compact powder materials into solid composites, enhancing density and mechanical properties.

These manufacturing processes are critical in determining the lifecycle and performance of polymer composites in their respective applications. The authors emphasize that advancements in these technologies contribute significantly to the development of composites with superior mechanical properties, heat resistance, flame retardancy, impact resistance, and corrosion resistance.

6. APPLICATIONS OF 3D PRINTED MATERIALS

6.1. Tribological applications

Recent scientific studies have explored the tribological applications of 3D-printed components, particularly focusing on materials like PEEK, ABS, PLA, PCL, and Co-Polyester.

For instance, the article [59] by Friedrich provides a comprehensive review of polymer-based composites used in tribological (friction and wear) applications. It explores the mechanical, thermal, and wear properties of various polymer composites, emphasizing fiber-reinforced and nano-filled materials. The study discusses the impact of fillers, lubricants, and surface modifications on friction performance and durability, with applications in automotive, aerospace, and industrial machinery. The findings highlight the potential of advanced polymer composites in replacing traditional metal-based components in high-wear environments.

In [60], a comprehensive resource, Tyagi et al. delve into the intersection of additive manufacturing (AM) and tribology – the study of friction, wear, and lubrication. This book examines how various 3D printing processes influence the tribological properties of materials, including polymers, metals, and ceramics, providing insights into optimizing these processes for enhanced performance. It discusses the impact of reinforcing materials, such as carbon fibers and natural fibers, on the wear resistance and frictional properties of 3D-printed parts. In addition, the role of surface structures and treatments in improving the tribological characteristics of additively manufactured components is examined.

Lv et al. in [61] investigate the wear rates and friction coefficients of PEEK composites designed with alternating layered structures made by FDM technology under various loading conditions. The study exhibited improved tribological properties, including lower wear rates and reduced friction, suggesting potential benefits for applications requiring enhanced durability and performance.

Additionally, Liu et al. [62] examined the tribological behavior and failure mechanisms of PEEK-based composites, Babbitt alloy, and CuSn10Pb10 bimetal for wind turbine main shaft sliding bearings under simulated operational conditions, providing insights into their suitability for high-load applications.

Furthermore, Maslavi et al. [63] determined the "tribological performance working fields" for pure PEEK and PEEK composites under dry sliding conditions, aiding in the optimization of material selection for specific applications.

The article by Roy and Mukhopadhyay [64] titled investigates the wear and friction characteristics of 3D-printed components made of ABS and PLA. Tribological tests were performed on specimens under varying loads and sliding speeds to assess the materials' wear rates and friction coefficients using a pin-on-disc apparatus, where the 3D-printed samples served as the disc, and a hardened steel pin acted as the counter face. PLA exhibited higher friction coefficients compared to ABS. However, ABS samples showed greater wear resistance than PLA. The findings suggest that ABS may be more suitable for applications requiring better wear resistance, while the higher friction of PLA could be advantageous in scenarios where increased grip is desired.

Ramadan et al. in the article [65] investigates the wear and friction characteristics of four commonly used 3D-printed polymers: PCL, ABS, PLA, and Co-Polyester. The study employed FDM to fabricate disc test specimens with a 100% infill density, ensuring maximum material consistency. Tribological assessments were conducted using a pin-on-disc apparatus varying loads and sliding speeds. Additionally, Vickers hardness testing was performed. ABS and PCL samples exhibited the highest coefficients of friction, while PLA and Co-Polyester demonstrated lower values. ABS has surpassed other materials in terms of wear resistance. A 100% infill density contributes to a smoother friction coefficient.

The article [66] by Gbadeyan et al. provides a comprehensive review of advancements in the tribological performance of 3D-printed polymer nanocomposites. It describes the incorporation of nanoparticles into thermoplastic matrices, emphasizing how particle size and distribution influence wear resistance and frictional behavior, highlighting how printing parameters affect the microstructure. Various abrasion testing methodologies are reviewed, providing insights into how applied load, sliding speed, and distance affect the tribological performance of both pure thermoplastics and particle-filled composite.

Sukri et al., in article [67], investigates enhancing the wear and friction characteristics of 3D-printed PLA components through the incorporation of graphite particles during the printing process.

A suspension in ethanol of graphite flakes of 40 μm size was applied to the top layer of 3D-printed PLA specimens. An increase in roughness from 0.573 μm for unmodified PLA to 1.187 μm of graphite-enhanced PLA was found. The graphite-enhanced PLA specimens demonstrated a noticeable decrease in the coefficient of friction and an enhanced wear resistance.

6.2. Testing methods of 3D-Printed Gears

Recent scientific studies have employed various testing methods to evaluate the performance and durability of 3D-printed gears. These methods are crucial for understanding the wear characteristics, strength, and overall reliability of gears produced through additive manufacturing. Below is an overview of notable testing approaches and the corresponding sources.

Wear Testing. Researchers have developed specialized gear wear test rigs to assess the wear performance of 3D-printed polymer gears. In article [68], the wear assessment performed for prototype gears made of PET-G filament was carried out by two methods – inspection based on visualization of the cross-sectional geometry of the gears and statistical characterization of selected kinematic parameters and torques generated by the drives. In [39], Roy et al. analyze gears made of ABS M-30, ULTEM 9085 (PEI) and PEEK in terms of economical application and strength parameters. The study [72], Dogan et al. investigated gears made from different polymer materials, analyzing the effects of drive side pressure angles (DSPAs) on wear behavior under various pinion speeds and torques.

Accelerated Wear Testing. To expedite the evaluation process, accelerated wear tests have been performed on gears printed from materials like ABS, PLA, and annealed PLA. These tests utilized specialized rigs designed to simulate extended operational periods within a shorter timeframe, allowing for rapid assessment of wear resistance and durability [73] (Poltocra).

Fatigue Tests. The article [37] by Pisula et al. investigates the fatigue using a test rig special designed and the wear characteristics of spur gears fabricated through additive manufacturing techniques, specifically FDM and FFF of materials ABS, PEI and PEEK. It reveals that PEEK is resistant to wear when operates at temperature, the biggest wear being measured for gears made from Ultem 9085.

Dimensional Accuracy and Surface Finish Assessment. The geometric accuracy and dimensional precision of 3D-printed gears are critical for proper meshing and function. Studies have employed advanced metrological techniques to evaluate parameters such as straightness, roundness, and surface roughness. By optimizing printing parameters—including layer thickness, extrusion speed, and print temperature—researchers aimed to enhance the accuracy of gears produced via Fused Deposition Modeling (FDM) [69] [83]. In surface topography analysis, techniques such as scanning electron microscopy (SEM) and optical profilometry are employed to capture detailed images and measurements of the gear tooth worn surfaces [71].

Surface Durability Testing. Experimental setups have been designed to test the surface durability of 3D-printed polymer gears, especially under non-lubricated conditions. Factors such as sliding speed, material hardness, surface finish, and microstructure were considered [70]. Gears are operated over extended periods under specific loads and speeds. Periodic inspections are conducted to measure wear depth, surface roughness, and material loss [71].

Parametric Studies and Contact Strength Analysis. Comprehensive reviews have highlighted the importance of tailored design considerations for 3D-printed spur gears. Analytical, numerical, and experimental methodologies have been employed to evaluate contact stress, tooth bending strength, and impact resistance. These studies underscore the significance of optimizing gear design parameters to ensure adequate contact strength and reliable performance [84].

In the comprehensive review by Pujari et al. [71], several experimental methodologies are discussed to evaluate the performance and durability of 3D-printed gears. The key experimental approaches highlighted include:

Contact Stress Analysis. Experimental setups often involve applying controlled loads to gear pairs and measuring the resulting stress using sensors or pressure-sensitive films. These measurements help in validating theoretical models and finite element analysis (FEA) simulations.

Tooth Bending Strength Evaluation. Gears are subjected to incremental loading until tooth failure occurs. The bending strength is then calculated based on the applied load and the gear's geometric parameters.

Impact Resistance Testing. Drop-weight testers or pendulum impact testers are used to apply sudden forces to the gear teeth, and the resulting damage or deformation is analyzed.

Dynamic Performance Evaluation. Method: Gears are integrated into test rigs that simulate real-world operating conditions. Sensors measure parameters like vibration amplitude, acoustic emissions, and torque transmission efficiency.

6.3. Aerospace Applications

Kobenko et al. investigates in [74] the feasibility of using additive manufacturing (AM) to produce aircraft interior aircraft interior spare parts: a class divider and a folding table made by FDM of Ultem 9085, known for its high strength-to-weight ratio and flame resistance focusing on their structural integrity. Finite element analysis (FEA) identified that increasing the width of the class divider would enhance its bending stiffness, thereby improving its structural integrity. Physical tests were performed to validate the simulation results as concerns mechanical properties, structural integrity, and performance.

The study on Ultem 9085 by Ng and Brennan [37] focuses on its application in high-temperature and radiation-exposed environments, making it particularly relevant for aerospace applications (e.g., aircraft and spacecraft components requiring heat and radiation resistance) and for nuclear industry (e.g., structural parts exposed to radiation), defense and military (e.g., equipment used in extreme operational conditions), high-performance engineering (e.g., specialized enclosures or housings in harsh environments).

6.4. Molds and Dies

Article [38] by Zaragoza et al. investigates the feasibility of using 3D-printed polymeric tools in the air bending process of sheet metals, aiming to offer cost-effective and flexible tooling solutions for small production batches. The study focused on two thermoplastic materials, Polycarbonate (PC) and Polylactide (PLA). Special designed V-die tools were employed in air bending experiments to form sheet metal components. The performance of the polymeric tools was assessed based on factors such as dimensional accuracy, surface finish of the bent parts, and tool wear over repeated operations. PC tools exhibited higher mechanical resistance and better durability compared to PLA tools, making PC more suitable for applications requiring higher strength and longer tool life.

Pelin G. et al. provide a comprehensive overview [75] of how additive manufacturing (AM) is utilized in creating polymeric molds across various applications. The use of 3D printing in mold fabrication can lead to creation of complex mold designs, reductions in material waste, production time, and overall costs, making it an alternative to conventional tooling processes. It discusses the application of 3D-printed polymeric molds in various fields, including: processes (injection molding, casting, thermoforming, and vacuum forming); composite fabrication (composite materials with complex geometries used in aerospace and automotive industries); biomedical engineering (3D-printed molds used to create scaffolds and implants); soft lithography (molds for developing microfluidic devices and other small-scale structures).

6.5. Tools for sheet metal cutting

The article [76] by Szalai et al. explores the application of Fused Deposition Modeling (FDM) 3D printing technology in the fabrication of cutting tools for sheet metal processes in the automotive and electronics industries. The study involved designing and manufacturing cutting tools using FDM 3D printing. These tools were then subjected to sheet metal cutting tests to evaluate their durability, precision, and overall effectiveness compared to conventional tools. Such tools used in sheet metal cutting proved to have real potential in this process offering benefits in terms of reduced production time and cost. However, considerations regarding material selection and tool design were identified as critical factors influencing tool performance and life.

6.6. Multi-materials

Vakharia et al. in the work [77] explore the use of fused filament fabrication (FFF) to create multi-material composites using ULTEM and carbon-fiber-infused ULTEM. Multi-material composites were fabricated with different layering patterns (e.g., AAABBB vs. ABABAB). The mechanical properties of parts were assessed revealing values between the single-material components (ensile strength of 59 MPa and an elastic modulus of 3.005 GPa). The print quality decreased from layers close to the heated bed to those nearer the top surface attributed to the thermal insulating properties of the material itself. The findings suggest that multi-material additive manufacturing using PEI-based polymers have potential benefits for aerospace applications.

The article [21] by Duan et al. introduces a novel approach to optimize fiber-reinforced composite structures by integrating multi-material and multi-scale design considerations. The study uses the Discrete Material Optimization (DMO) method and Variable Stiffness (VS) Design, which allow for effective material selection and structural design in composite panels. By adjusting the number of discrete fiber orientations, the study explores how these variations influence the mechanical properties and efficiency of the composite structures. The proposed optimization framework realizes clear macroscopic multi-material structural topologies and optimized orientations of microscopic fibers, which leads to improvement of structural performance and efficiency of materials used in composite structures with tailored properties for various engineering applications.

7. CONCLUSIONS

This article reviews the most recent thermoplastic materials used in FDM, more specifically FFF, with an emphasis on possible applications and trends in their evolution. It is found that the field is one with a very strong dynamic due to research on thermoplastic materials, but also on composite materials to improve mechanical characteristics, thermal and chemical resistance, dimensional stability, various applications, etc. Recent applications are presented that include thermoplastic materials used in various industries such as models of parts with complex structures that replace parts obtained through classical technologies (casting, hot and cold deformation, machining) bringing flexibility, reduced waste and costs.

It is clear that the quantities that characterize thermoplastic materials but also the process parameters are subject to changes from one manufacturer to another, but, at the same time, they obtain better values due to studies on the optimization of various process parameters or by creating composite materials with improved characteristics. Recent advancements in 3D printing with thermoplastics have broadened their applications across various industries. Notable developments include:

- The automotive industry, by producing lightweight, high-performance vehicle parts, increasing efficiency and performance; custom jigs, fixtures, and tooling, reducing production time and costs.
- Aerospace industry, by rapid prototyping and producing functional components, benefiting from the materials' strength-to-weight ratio and design flexibility.
- Medical Field, by personal protective equipment addressing supply shortages effectively; drug delivery systems, such as 3D-printed implants designed for targeted drug delivery directly to the affected zone.
- Customized footwear, such as 3D-printed shoes, offering customization and improved performance; protective gear, for example 3D-printed helmet inserts to reduce crowd noise for quarterbacks, enhancing on-field communication.
- Consumer Goods, by eyewear and electronics (3D printing customized eyewear frames and electronic device components); fashion accessories such as 3D printed unique accessories (jewelry and handbags).
- Architecture and Construction by complex architectural elements, offering design flexibility and reducing material waste; detailed scale models, facilitating better visualization and planning.
- Animal Prosthetics by developing 3D-printed prosthetics for animals, improving mobility and quality of life.

In addition, besides the advancements in 3D printing materials, technologies and their applications, their limitations are presented and critically reviewed.

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