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Mechanical Properties Of 3D Printed Carbon Nanofiber Reinforced Polyphenylene Sulfide Composites - A Comprehensive Review

Y C Arun[1], R. Ravishankar[1], Sriharsha Kumar[2], M.R Ramesh[3] and R Suresh[4,*]

[1]*Department of Mechanical Engineering SJCE, JSSSTU MYSURU – 570006, Karnataka, India,*

[2]*Department of Mechanical Engineering, Siddaganga Institute of Technology, Tumakuru-57210, India*
[3]*Department of Mechanical Engineering, National Institute of Technology, Surathkal Karnataka-575025, India*
[4,*]*Department of Mechanical and Manufacturing Engineering, M. S. Ramaiah University of Applied Sciences, Bangalore-560058, India*
**Corresponding Author: R Suresh, Email:sureshchiru09@gmail.com*
ORCID ID: https://orcid.org/0000-0002-6956-9751

Polyphenylene sulfide (PPS) is a high-performance, semi-crystalline polymer valued for its thermal stability, with a melting point of 285°C (545°F). It is chemically resistant, dimensionally stable, and maintains its mechanical properties under harsh conditions, making it ideal for automotive, aerospace, electrical, and electronics applications. PPS is used in components exposed to long-term heat, chemicals, or mechanical stress. While PPS is recognized for its thermal and chemical stability, limited reviews exist on carbon nanofiber (CNF)-reinforced PPS composites. Integrating CNFs into PPS can significantly improve the material's mechanical, thermal, and electrical properties, making it even more suitable for advanced engineering applications. However, synthesizing these composites involves challenges like the uniform dispersion of nanofibers and managing the CNF-PPS interface. Research on CNF-reinforced PPS composites is expanding, but further exploration of the advancements and challenges in this field is necessary. Such studies can help researchers and industry professionals understand the full potential and limitations of these composites, guiding future research and application development. This overview highlights how the integration of CNFs into PPS, combined with 3D printing techniques, enhances the composite's performance characteristics. It explores the composite's thermal stability, mechanical strength, and chemical resistance, showing how CNF-reinforced PPS can meet the stringent demands of industries like aerospace, automotive, and electronics, where advanced materials with superior properties are required.

Keywords: Poly-phenylene sulfide; Carbon nanofiber; 3D printing; Synthesis; Elastomer; Thermoset; Polyether.

1. Introduction

Chemical structure and physical behavior of polymers can be used to classify them into three main types: thermoplastics, elastomers, and thermosets. Thermoplastics are composed of linear or branched macromolecules and can undergo multiple cycles of melting and re-molding. In contrast, elastomers and thermosets keep their solid state as a result of their crosslinked molecular structure. Thermosets are distinguished by a highly crosslinked network with robust chemical bonds, and they can only undergo breakdown at elevated temperatures. [1]

In the last few years, there has been a notable research emphasis on thermoplastic polymers, particularly those with high-performance attributes, including exceptional thermal and mechanical properties. These polymers have attracted attention for their versatility and capacity to meet the rigorous requirements of diverse applications. In recent decades, aromatic-unit-infused high-performing polymers, such as polyether sulfone (PES) and polyether ketone (PEEK), as well as polyphenylene sulfide, have attracted considerable focus. Among these, PPS has emerged as a versatile engineering thermoplastic characterized by high strength and exceptional thermal properties. It is utilized extensively for thermoplastic composites like matrices, organic fibers, and molding resins.

PPS is well-regarded for its distinctive blend of environmental stability, mechanical strength, and thermal performance [2]. PPS finds applications across a diverse range of industries, comprised of precision instruments, chemicals, electronics, electrical appliances, automobiles, and aerospace. Its noteworthy properties position it as a preferred material for challenging applications in these sectors. Functioning as an engineering polymer, PPS meets stringent requirements regarding performance and reliability. Consisting of several thiophenyl units, PPS is recognized for its remarkable chemical stability and thermal oxidation resistance. One of the major benefits of this material is its exceptional strength and durability, combined with a relatively low weight. It also boasts impressive resistance to wear and tear, as well as similar chemical and heat resistance to other top-performing engineering plastics such as polyimide, polyarylester, and poly ether ketone (PEEK).

In addition PPS has better overall mechanical qualities in comparison to common or intermediate polymers such as polypropylene and polyamide [3]. Using repeated para-substituted rings and rigid, symmetrical sulfur atoms as its backbone chain, PPS is a semi-crystalline thermoplastic. This high-performance polymer is remarkable, with a melting temperature (Tm) of around 285°C and a glass transition temperature (Tg) of about 90°C [4]. Renowned for its exceptional physical and chemical properties, PPS has exceptional anti-aging capabilities, enhanced hardness and stiffness, intrinsic flame resistance, dependable chemical resistance, high temperature stability, and remarkable friction features [5]. The Properties of PPS materials is tabulated in Table 1. The PPS thermoplastic polymer, primarily owing to its low melt viscosity (approximately ~200 Pa.s), facilitates molding with substantial filler or reinforcement contents. In numerous instances, PPS products are improved with glass or carbon fibers to reach higher performance levels, especially in applications related to electronics, automobiles, and aircraft [6]. Also, in the aerospace sector PPS reinforced with carbon fiber (CF/PPS) is mostly utilized in structural applications.

2. Materials and methods

Carbon nanofiber (CNF), it is a important component of carbon fibers, which is used for both industrial and for scientific exploration. Carbon nanofiber (CNF) composites exhibit promise as materials for a range of applications, such as sensors, batteries, and supercapacitors, as well as electrical devices. Electrical conductivity is taken very seriously in these applications. CNFs have sizes between 50 and 200 nm, which is a larger range than that of ordinary carbon fibers (CF), which have dimensions in the range of several micrometers. Beyond variations in dimension, CNF structures differ significantly from conventional carbon fiber constructions. The sources for traditional carbon fibers are typically meso-phase pitch (MP) or high-strength polyacrylonitrile (PAN). The preparation circumstances of these fibers, such as the oxidation environment, raw material selection, and heat treatment temperatures, affect their characteristics. Unlike traditional carbon fibers, carbon nanofibers (CNFs) are mainly made by electrospinning and catalytic vapor deposition growth [7].

Table 1. Properties of PPS materials

Physical properties of PPS	Unit Values
Vickers microhardness of the material	24 kg/mm^2
Melting temperature of the material	280 °C
Density of the material	1350 kg/m^3
Coefficient of thermal expansion (x10-6/ °C)	51.6 (<Tg), 97.9 (>Tg)
Electric conductivity of the material	1.5 x 10^{-6} (S/cm)
Thermal conductivity (k) of the material	0.22 W/mK
Dielectric strength of the material	22-28 kv/mm

2.1 Synthesis and structure of PPS

2.1a. Chemical route

Ease of use and simplicity of the oxidative polymerization method for diphenyl disulfide are well-known. Another workable method for producing PPS is to use Lewis acids to polymerize diphenyl disulfide. Several Lewis acids, including SbCl5, MoCl5, and TiCl4, can be used to carry out this polymerization process. The chosen Lewis acid-to-oxidant ratio has a major impact on the final structure, morphology, and transport characteristics [8]. In order to attain the best possible PPS yield, it is necessary to adjust the ratio of Lewis acid to monomer in the chemical process. The yield of PPS is affected by temperature, decreasing as the temperature rises [9].

To produce PPS, one usually combines sodium sulfide (Na2S.9H2O) with halogenated aromatic materials like p-dichlorobenzene. This reaction happens in an aprotic organic solvent, while the environment is filled with nitrogen. Furthermore, in nitromethane, diphenyl disulfide and aluminum trichloride can react at ambient temperature to produce a white powder with the empirical formula C6H4S that is soluble in heated N-methylpyrrolidone [10]. When the temperature rises, the PPS yield for the diphenyl disulfide polymerization drops to about 50%. In the polymerization, the ideal concentration of SbCl5, MoCl5, and FeCl3 is double the equimolar amount of diphenyl disulfide. On the other hand, for effective PPS production, AlCl3, TiCl4, and BF3O (C2H5)2 need more than ten times the equimolar quantity of the monomer [11].

Melting point, indicative after the polymer yield stabilizes, the polymer's molecular weight rises. PPS is produced when the generated polymer or oligomers react with Lewis acid, indicating a stepwise polymerization process. It is thought that the cations support a cationic process by electrophilically reacting with diphenyl disulfide to produce the trimer. Due to substituents that donate electrons, poly (methyl-substituted phenylene) is generated more quickly during polymerization than PPS [10].

2.1b. Electrolysis

Set of platinum plates, serving as both the working and auxiliary electrodes, were positioned within the cell with a 1-cm spacing. The reference electrode utilized was Ag/AgCl. The experimental setup involved a nitromethane solution containing thiophenol (ranging from 0.1 to 1 mol), along with a Lewis acid, maintained at a temperature of 20°C in an environment of nitrogen. Under regulated prospective circumstances, the preparative electrolysis process was carried out [10].

2.2 Synthesis and structure of CNF

Several ways to prepare CNF will be discussed in this section. In current times, there are two main methods utilized in the production of CNF. The first involves electrospinning and subsequent heat exposure, while the second technique is thermal chemical vapor deposition (CVD) using catalyst.

2.3 CNF produced with the advancement of chemical vapor deposition using heat catalytically

CNFs come in two forms: platelet and cup-stacked. These distinct forms are produced by thermal chemical vapor deposition technique using catalyst. In 1994, Sattler and Ge came across a cup-stacked CNF, also known as the conical CNF. The process used to construct cup-stacked CNFs is illustrated in Figures 1 (a-c), while Figure 1 displays the structures of platelet CNFs [11].

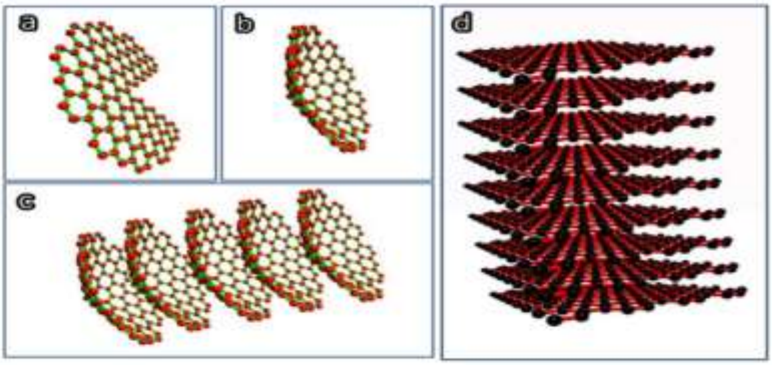

Figure 1. Diagrammatic representation of the formation of [d] platelet CNF structure and the [a—c] cup staked CNF structure [11]

In the catalytic vapor deposition growth process for CNF synthesis, a variety of metals and alloys have been used as catalysts due to their ability to dissolve carbon and produce metal carbide. These catalysts include vanadium, chromium, nickel, cobalt, and iron. Within the temperature range of 700–1200 K, the process employs many carbon sources, including molybdenum, methane, carbon monoxide, synthesis gas (H2/CO), ethyne, or ethene [12]. The catalytic nanoparticles' morphology affects the CNF's structural design. The build-up of dissolved hydrocarbons in the metal particles, which precipitate as graphitic carbon on the metal surface, is the mechanism underlying the growth of CNF.

2.4 CNF ready via Electrospinning

Electrospinning is a well-known technique for manufacturing CNF. This review presents an overview of the structure and characteristics of CNFs produced through electrospinning and subsequent carbonization. In order to create CNFs using electrospinning, precursors like polymer nanofibers are necessary. The quality of the final

CNFs are highly dependent on the type of polymer solution and processing conditions used. Pitch and polyacrylonitrile (PAN) are two commonly used polymers, while others like poly (vinyl alcohol) (PVA), polyimides (PIs), polybenzimidazole (PBI), poly (vinylidene fluoride) (PVDF), phenolic resin, and lignin are also utilized [13]. Following preparation procedure is completed successfully; the polymer nanofibers are carbonized to produce CNFs using heat treatment. The environment and temperature during the heat treatment process determine the final CNFs' shape, purity, crystallinity, diameters, and porosity. Figure 2 displays the electrospinning equipment employed to produce CNF. After polymer nanofibers are successfully fabricated, they must be heated to 1000°C in a certain atmosphere for the carbonization process to take place. The diameter of the CNFs often decreases as a result of volume and weight changes that take place during carbonization [13].

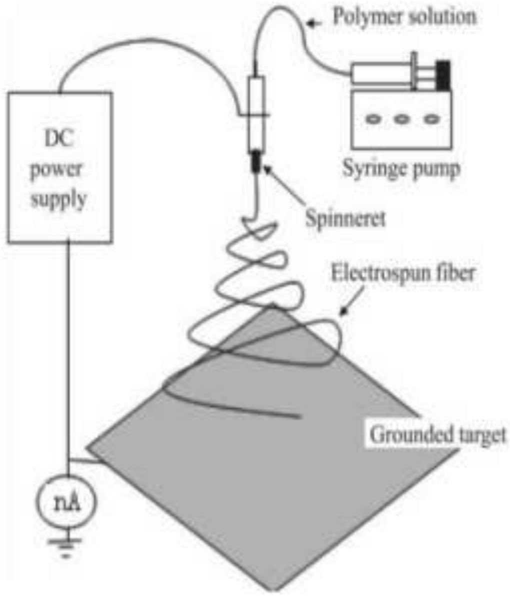

Figure 2. Diagrammatic illustration of the electrospinning apparatus used to fabricate CNF

2.5 Fabrication using 3d printing for PPS/CNF polymer composites

Process of creating objects by layering materials together using 3D models is commonly referred to as 3D printing. There are several other terms used to describe this process, such as additive manufacturing, rapid prototyping, and solid-freeform [14]. This innovative technique adds materials incrementally, minimizing waste and achieving precise geometric precision. Initially, a 3D computer model that has been meshing is constructed. This can be done by using CAD software to develop designs or by using picture data that has been recorded. Surface Tessellation Language (STL) files are frequently produced as a result of this. The mesh data is then divided into a building file with two-dimensional layers, and this file is sent to the robot that uses 3D printing to produce the object [15].

Various materials find application in 3D printing, and in the realm of polymers, their uses are manifold. In the field of aeronautical engineering, polymers are used to create complex lightweight constructions [16], in architecture to create structural models [17], in part to replicate objects or teach lessons, and to print tissues and organs in medicine. But not all 3D-printed polymer products are utilized as functional parts; the majority are utilized as conceptual prototypes. The main issue lies in the fact that when it comes to 3D printing, polymer products made from pure materials often lack the durability and practicality necessary to function as load-bearing parts. As a result, the use of 3D printed polymers in industry is not yet prevalent due to these limitations. The combination of the matrix and reinforcements yields a system that exhibits improved characteristics in terms of structure and function.

Polymer composites printed three dimensionally overcome such problems that cannot be achieved by either component alone [18]. The process of creating polymer matrix composites, which exhibit exceptional mechanical performance and usefulness, includes the incorporation of fiber, particle, or nanomaterial reinforcements into polymeric materials. Conventional methods for making composite material, including casting, molding, and machining involve the removal of material to create products with complex geometries [19]. While these techniques provide well-managed and comprehended manufacturing processes and performance, they have limitations in controlling the complex internal structure of composites. On the other hand, sophisticated composite structures can be produced via 3D printing without the typical waste of materials. The complete control over the geometry and size of these composites is made possible by computer-aided design (CAD). There is no better combination of process flexibility and high performance product output when it comes to 3D printing composites.

2.6 Modelling using fused deposition (FDM)

Printed polymer composites with the most widely used printers are those that use fused deposition modelling, or FDM. Because of their lower melting temperatures, thermoplastics including PC, ABS, PLA, and PPS are frequently selected. Figure 3 shows Controlled extrusion of thermoplastic filaments is a prerequisite for the functioning of FDM printers. The filaments partially melt at the nozzle during the FDM process, after which they are carefully extruded, layer by layer, onto the build platform. Once the layers have been laid down, they meld together and solidify to form the final product [20]. To produce satisfactory results in 3D printing, several printing parameters can be altered to regulate the quality of printed components. Some of these parameters are air gap, raster width, raster angle, printing orientation, and layer thickness. However, one major disadvantage of FDM printing is that composite materials need to be accessible in filament form in order to be extruded effectively. Challenges arise in uniformly dispersing reinforcements and eliminating voids that may form during the production of composite filaments [21]. Additionally, the materials that FDM printers can work with are limited, mostly to thermoplastic polymers that have the right melt viscosity. This viscosity needs to be balanced; it needs to be both low enough to enable efficient extrusion and high enough to support the structure. To eliminate each support structure during printing is challenging.

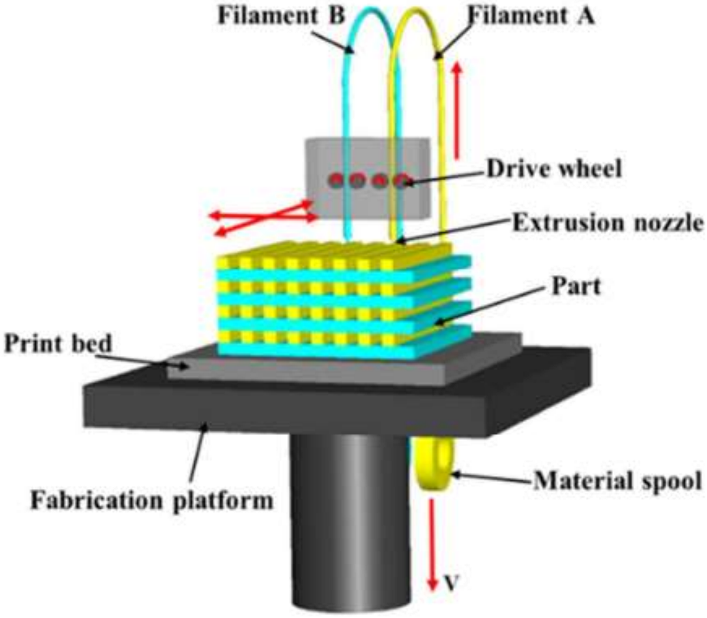

Figure 3. Schematic demonstration of a typical FDM Process

FDM printers have clear benefits despite these drawbacks, including as affordability, quick printing times, and ease of use. Another noteworthy benefit of FDM printing is its potential for depositing many materials at the same time. FDM printers are equipped with many extrusion nozzles that are filled with different materials. It becomes possible to create multifunctional printed parts with specifically designed compositions.

2.7 Fiber reinforced polymer composites

Fiber reinforcements are important for improving polymer matrix materials. Two well-liked 3D printing methods for fiber-reinforced polymer composites are direct writing and FDM. FDM involves the extrusion of blended polymer pellets and fibers into filaments; occasionally, a second extrusion is necessary to achieve uniform fiber distribution. Fibers and polymer paste are combined for direct writing, after which the fibers are directly extruded. Because it might be difficult to achieve a smooth powder-fiber mixture, fiber-reinforced composites are not best served by powder-based processes [22].

In 3D printing, short fibers like carbon and glass are commonly utilized to reinforce mechanical qualities. The final composite's characteristics are mostly determined by the fiber orientation and void fraction. Because of gaps and poor polymer-fiber bonding, 3D printed composites frequently include gaps, while compression-molded samples have few pores. However, because printing aligns more fibers in the direction of load bearing thereby offsetting porosity the increase in tensile strength in printed samples roughly resembles that of compression-molded materials [23]. The mechanical characteristics of fiber-reinforced polymer composites are tabulated in Table 2.

Optimal performance is usually achieved with greater fiber content, with a 5%weight fiber loading can increase porosity and varies in effectiveness among different cases due to differing fiber distribution and interfacial bonding. Establishing basic standards for design and processing may be necessary [24]. While fiber content additions have reached up to 40 wt%, further increases face challenges such as nozzle clogging and loss of toughness when making continuous filaments for FDM. Low fiber content thus places restrictions on the final composites' characteristics. Using plasticizers and compatibilizers could help with understanding increasing the amount of fiber and printing materials rheological characteristics. An additional difficulty with printing using fibers is integrating continuous fibers, as most research has focused on short fibers within the polymer matrix. Nevertheless, some recent studies have explored continuous fiber-based printing [25].

Table2. The mechanical characteristics of fiber-reinforced polymer composites

Technique	**Material**	**Fiber loading**	**Max tensile strength (MPa)**	**Tensile Strength improvement in % compared to that of raw polymer**
Direct write	Short glass fiber/ Epoxy	34.5 wt%	464.4	446
FDM	Short glass fiber/ ABS	18 wt%	58.6	140
FDM	Short glass fiber/ ABS	40 wt%	70	115

3. PPS morphology

Thermoplastic polymer PPS, that is semicrystalline. Like all semicrystalline polymers, it has phases that are both amorphous and crystalline in nature [26]. The morphology of PPS is covered in this section based on the following sections:

1) The nucleating agent's effect
2) The role of fibers in composite materials
3) The connection between mechanical characteristics and the crystalline phase.

3.1 Impact of Nucleating Agent

In actuality, fillers or additives (such as fibers or nanotubes) may act as nucleation sites on the surface where nucleation can start. Jiang et al. [27] explore the effect of hydroxyl-purified multi walled carbon nanotubes in PPS composites. He created more composite material by mixing PPS with multiwalled carbon nanotubes at 1%, 2% and 3%. They showed that while the crystallization temperature fell sharply in tandem with the rise in multiwalled carbon nanotube content the composite materials' enthalpy ΔH_c increased. Furthermore, the melting point and glass transition temperatures did not significantly alter when carbon nanofiber was added to PPS, however the crystallization temperature did somewhat drop [28] is as in Figure 4. Based on Figure 4 and Table 3 results, it can be inferred that crystallinity decreased with increasing CNF fraction. This is mostly because CNF has a tendency to obstruct PPS molecules ability to arrange themselves in an ordered manner.

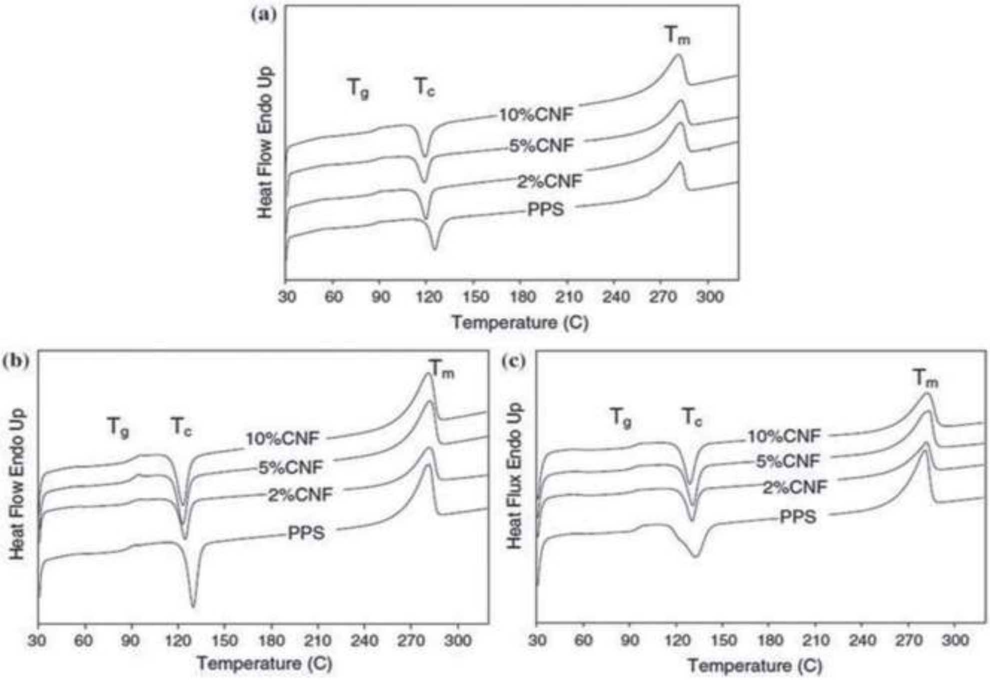

Figure 4. PPS-CNF composites: Differential Scanning Calorimetry (DSC) study in relation to heating rate: A) 5 °C min−1 [28].

Table 3.Effects CNF on the DSC analysis's thermal characteristics

Sample	**Heating rate (^{O}C/min)**	**T_g(^{O}C)**	**T_c (^{O}C)**	**T_m (^{O}C)**	**ΔH_c (J/g)**	**ΔH_c (J/g)**	**X_c (%)**
PPS	5	83.9	125.1	281.9	39.5	59.5	16.3
PPS-2% CNF		83.5	119.9	282.3	16.9	34.1	14.6
PPS-5% CNF		84.5	118.3	282.1	18.6	34	13.6
PPS-10% CNF		84.7	120.3	281.9	17	29.6	11.9
PPS	10	84.8	129.5	281	38.8	60	16.7
PPS-2% CNF		85.4	124.2	281.5	23.8	42	15.4
PPS-5% CNF		86.5	123	281.8	20.2	35	13.1
PPS-10% CNF		85.9	123.8	281.5	16.5	30	12.7
PPS	20	86.6	132.6	281	29.3	45.6	13.5
PPS-2% CNF		86.4	130.6	281.8	27.8	41.9	12
PPS-5% CNF		86.2	130.9	282.5	19.6	33.4	12.2

PPS-10% CNF	87.1	129	282.2	17	27.1	9.6

3.2 The Impact of Fibers in Composites

The degree and the kind of crystallization for any thermoplastic polymer can generally be altered by its heat history. But in composites that have fiber reinforcement, the fibers may also have an impact on the morphology. A study conducted by [28] examined the PPS composites' isothermal crystallization process after melting that were not reinforced, as well as PPS composites that were modelled as carbon and aramid, and fiberglass reinforced. The findings showed that both surface treatment and the fibers themselves influenced how much of an impact they had on PPS crystallization. The fibers can also serve as a crystallization nucleation site, as we previously described, and this could have an impact on the crystallization process.

3.3 The Connection between Mechanical Properties and the Crystalline Phase

It is commonly recognized that mechanical characteristics can be directly impacted by crystallization behaviours. The link between crystallinity and impact attributes revealed that, for PPS blends, the impact strength increased as crystallinity decreased. Furthermore, Nishihata et al. [27] examined fracture toughness. The specimens utilized in the study were linear, branched, and heat-treated PPS. The analysis indicated that linear PPS exhibited greater fracture toughness than the heat-treated and branched versions, and that the degree of crystallinity influenced the fracture toughness. It is important to note, however, that the PPS types utilized in this reference differ, and a monotonic tendency cannot be used to deduce about the impact of crystallinity on fracture toughness.

3.4 PPS Processing

PPS has a relatively high melting point (285 °C), and molding of PPS occurs at a high temperature [28]. It's crucial to have a molding process that minimizes the time PPS is being molded in order to prevent the polymer from breaking down. PPS processing could be explained as follows: Polyphenylene sulfide was compressively molded to take on some of the necessary shape after initially being mixed with the selected filler. After that, this component is freely sintered by being baked at a temperature that increases gradually and being cured for a while. The part is cooled and ready for use following the curing procedure. Injection molding provides challenges when working with virgin PPS. The use of a shutter nozzle and mold curing sealing will be necessary due to its high fluidity when molten. In addition, direct sheet formation occurred from the filaments drawn by an air stream moving quickly. This sheet's exceptional chemical and thermal qualities make it suitable for usage as heat-insulating materials and industrial filters. Also displayed in Table 4 are the characteristics of injection-molded PPS thermoplastics [28].

Table 4. Characteristic of injection molding PPS

Material property	**PPS**	**PPS/Glass Fiber (60/40)**
Specific gravity	1.35	1.65
Tensile strength in MPa		
At 21°C	64-77	150

At 204°C	33	33
Flexural modulus at 21°C in MPa	4200	15500
Elongation at break in %	3	2-3
Dielectric constant in (10^3-10^6 Hz)	0.004	0.0037
Volume resistivity in Ω cm	2.5×10^{16}	2.5×10^{16}
Dissipation factor in (1kHz)	0.004	0.0037
Water absorption in %	< 0.02	< 0.05

3.5 Blending

A greater number of polymers are being synthesized and used in a wider range of applications as society and the economy grow. These, however, are insufficient to satisfy the increasing need for polymers with various mechanical, electrical, thermal, and tribological characteristics. Thus, to maximize the utilization of various polymers, blends and composites are produced. We specifically give the polymer blends, particularly those with compositions comprising PPS, extra consideration in this section.

As was already established, neat PPS presents challenges for injection molding and is somewhat brittle with low impact strength. Thus, numerous strategies have been put out to get around PPS's drawbacks. The most popular and widely used technique in the industrial and academic realms at the moment is to physically blend or alloy PPS with other polymers or with other reinforcing materials. As a result, we introduce the changes in this part depending on the three elements listed below:

1) Polyphenylene sulfide mixed with various polymers
2) Polyphenylene sulfide blending with nanotubes at the nanoscale area

3.6 Combining polyphenylene sulfide with other polymers

In their study, Lim et al. [29] examined the phase morphology and thermal properties of secondary blends composed of polycarbonate and PPS. Their findings showed that the addition of PC to PPS polymer resulted in a significant reduction in the melt viscosity. Meanwhile, reference [30] documented the behaviour of melting of PPS, PPS mixed with polysulfone and polyetherketone with phthalidydene groups. The results explore the melting temperature (T_m) and melting time (t_m) increases, the lesser melting peaks of PPS had intensified. The unique structure of Polyphenylene sulfide, which maintains the melting crystal lesser from becoming higher heating crystals and vice versa, may account for these observations. Additionally, Oyama et al. [31] examined more-combinations of performance-reactive materials that comprised polyphenylene sulfide. They noticed that the reactive PPS combinations showed exceptional 400°C thermal stability. Researchers are quite concerned about the crystallization behaviors of polymers combined with PPS, nevertheless. The thermal and crystallization properties of engineering polyblends, namely glass-reinforced PPS with polyethylene terephthalate led to an increase in PET's degree of crystallinity while it decreased in PPS.

Additionally, the scientists examined the mechanical properties of mixing polyphenylene sulfide PPS with various polymer materials. Zeng and colleagues studied the mechanical behaviour of polyphenylene sulfide PPS blended with acetylene-terminated sulfone, the interlaminar shear strength and flexural modulus of continuous unidirectional carbon fiber composites with a mixed matrix of ESF/PPS = 10/90 were found to be significantly greater than those with a pure PPS matrix. A study on polyphenylene sulfide/PPE alloy found that the microdispersion of polyphenylene ether had an impact on its mechanical behaviours, as an increase in particle diameter resulted in a significant reduction in PPS/SG/PPE weld strength. Tang and team synthesized SEBS and sebsg-MA for blends of PPS/PA 66, demonstrating that elastomers greatly increased the toughness of PPS/PA66 blends.

3.7 PPS Combination at the Nanoscale Range with Nanotubes

Numerous research projects have focused on the mixing of carbon nanotubes in nanoscale environments. By using melt compounding, Yu et al. [32] created PPS nanocomposites reinforced with multiwall carbon nanotubes (MWCNTs). The results showed how adding carbon nanotubes to PPS greatly increased the thermal stability of this nanocomposite. In a similar vein, Yang et al. [33] synthesized and studied PPS/MWCNT composites using melting chemicals, and they came to the conclusion that the generated composites' structure and chain mobility may be affected to some extent by the multiwall nanotube concentration. More specifically, when multinanotubes were added to PPS, they observed a considerable rise in Tg and the storage modulus. Furthermore, PPS/multiwall nanotube composites were examined from a physical point of view in the study reported in reference [33]. The study found that because of their strong affinity, the multiwall nanotubes were completely distributed throughout the PPS matrix, particularly at modest loading levels. Tensile characteristics and dynamic thermal mechanical properties can both benefit from the presence of multiwall nanotubes.

The scientists found that adding BP to the polymers boosted their breakdown temperature, as revealed by the TGA analysis. The mechanical characteristics of carbon nanotube/PPS composites were also investigated in this paper. They discovered that incorporating both nanofillers improved the stiffness and strength of the composites. Yu et al. [34] employed melt compounding to produce MWCNT reinforced PPS nanocomposites and discovered that the inclusion of CNT friction improved the materials' mechanical and thermal properties. The study found that the nanoparticles which are having spherical shape reduced contact between sections of polymers. The increased surface area where the SWCNTs and matrix meet was beneficial in stopping the PPS chains from spreading out, thus leading to a higher glass transition temperature.

The results of the experiments conducted showed that hybrid composites that contain both nanofillers in appropriate proportions shows good mechanical performance than composite materials that are reinforced with SWCNTs are wrapped in PEI. When it comes to the study of tribology, a greater interfacial contact area signifies that the SWCNT will probably have a larger point of contact with the matrix. As a result, this larger point of contact can lead to increased friction between the carbon nanotube and the matrix. This finding offers an explanation for the observed phenomenon. The mobility of PPS macromolecule chains is restricted by the increased contact area, which hinders their movement. Han et al. [35] produced PPS/multiwalled carbon nanotube composites by using the melt mixing technique. Their study revealed that the viscosity of the PPS/MWCNT composites became more complex due to the uniform dispersion of MWCNTs in the polymer matrix. Similarly, Pickering et al.

[36] produced polyphenylene sulfide/multi walled carbon nanotube (MWCNT) composites and used DMA to establish that PPS had a higher Tg and storage modulus.

4. Mechanical Properties and Applications:

4.1 Factors Influencing Fiber Reinforced Composites

Generally speaking, fiber can be classified as plant, animal, or mineral based. All plant fibers have important structural elements, but animal fibers contain protein. Furthermore, compared to accessible animal fibers, high-performance plant fibers have substantially better strengths and stiffness. In contrast, the use of natural fibers derived from minerals is less common because of the health risks connected with ingesting carcinogenic compounds. Thus, when it comes to creating composites with superior structural strength, plant fibers reign supreme as the most commonly utilized and fitting option.

4.2 Matrix Selection

The matrix is a crucial component of a fiber-reinforced composite, as it helps to counteract the harsh effects of environmental factors such as heat and chemicals. Polymeric materials are frequently employed in commercial applications due to their exceptional ability to withstand low processing temperatures and their light weight.

4.3 Fiber-Matrix Adhesion

Fiber-reinforced polymer composites contain fibers that can transfer force. The strength of the fiber-matrix connection is a crucial element affecting the mechanical characteristics of composites. Plant-based fibers may experience inadequate bonding and related difficulties since the fibers are hydrophilic and the resin is hydrophobic. Several methods have been suggested for this purpose, such as interlocking, chemical bonding, diffusion connection, electrostatic connection, and the application of coupling agents or chemical pre-treatment.

4.4 Fiber Dispersion

The length (long or short) of the fiber and processing variables (temperature and pressure) affect the fiber's dispersion. A good bonding is favoured by good fiber dispersion. This may make better mechanical characteristics [37].

4.5 Fiber Orientation

The mechanical properties of composites are often optimal when fibers are aligned in the direction of the applied force. When the fiber orientation is increased in relation to the fiber loading, the modulus and strength can be lowered. Various physical processes, including damage spread and self-heating, are associated with different moduli and strengths.

5. Mechanical characteristics of PPS and PPS composites

5.1 General PPS and PPS Composite Mechanical Behaviors

The mechanical characteristics of PPS and PPS composites are the main topic of discussion in this section [38]. More studies have been conducted which is based on the mechanical characteristics of composite materials based on polyphenylene sulfide.

The following themes are covered by these studies:

1) Behaviour under tensile and impact tests.
2) Behaviour under bending or flexing.
3) Behaviour under shear.
4) Behavior under compression.
5) Behaviour under fatigue.

5.2 Impact Test Behaviour and Tensile Behaviour

Environmental factors typically have an impact on tensile behaviour of PPS composites with glass reinforcement. The material's mechanical properties displayed exceptional performance at high temperatures beyond the glass transition point because of its lengthy glass reinforcement and high crystallinity. Heat treatment affected the mechanical characteristics of PPS composites reinforced with glass fiber, according to Zhai et al. [39]. Furthermore, the investigation looked at how temperature affects mechanical characteristics. The findings demonstrated a discernible rise in maximum stress and elastic modulus upon increasing the glass fiber content below the glass transition temperature of the PPS matrix. It indicates the PPS composites' highest stress point and modulus of elasticity at various temperatures.

Additionally, PPS is frequently utilized as a matrix in composite materials because of its high-performance capabilities, a fact that has been supported by numerous reports. Elastic-ductile behavior was observed in Carbon /polyphenylene sulfide laminates when it is subjected to loadings in tension, with a response that was significantly matrix-dominated. PPS resin exhibited a lower longitudinal stress and a more extended longitudinal strain at 120°C. When mixed with other polymers, polyphenylene sulfide exhibits remarkable mechanical characteristics, making it an excellent blending composition. Additionally, Pantelakis et al [40]. Investigated the tensile characteristics of polyphenylene composite which is reinforced with carbon fibers and discovered that thermal treatment significantly reduced the specimen’s tensile strength.

The investigation of the mechanical behaviors of PPS fiber materials after heat treatment. Furthermore, at temperatures between -40 °C and 180 °C, Garrell et al. [41] studied the mechanical characteristics of polyphenylene sulfide coupled with Nd-Fe-B permanent magnets. Their investigation revealed that PPS bonded magnets ultimate tensile strength dropped with temperature. Sinmacelik and associates [42] looked into the effects of exposure to ambient weather on the mechanical and surface characteristics of PPS composites in a related investigation. According to their research, weathering caused less of an impact strength reduction in fiber/particle-filled PPS composite than in short fiber-filled PPS composite. According to Kytyr et al. [43], ultrasonic wave propagation, frequencies, and bending stiffness were useful metrics for evaluating material degradation in C/PPS composites over time. The impactor's diameter had no discernible effect on the decrease in the elasticity module from three-point bending elasticity.

5.3 Bending or Flexion Behaviour

Under static loading circumstances, Yylmaz et al. [44] examined the load-bearing characteristics of pin-connected carbon/PPS composites. They found that a number of joint and material characteristics, such as connection geometry, fiber orientation, layer orientation, and pressure distribution along the plate thickness, had an impact on the bearing strength of the pin connection. Concurrently, a distinct investigation of the mechanical characteristics of composites made of polyamide 6 and PPS reinforced with carbon fibers. They discovered that while adding carbon fibers improved the strength and modulus, it had no effect on the impact strength or the pace at which the elongation broke. The authors of this study concluded that the addition of carbon fiber improved the bending modulus and bending strength and short carbon fibers were used to reinforce a PPS/polytetrafluoroethylene composite. Their findings indicated that the carbon fiber addition enhanced the bending modulus, hardness, and strength of the blends during tension.

5.4 Behaviour under shear

Structural elements are typically assessed using strengths of translaminar and interplane shear, as well as transverse stretch strength and ILSS to determine bonding quality. An essential use of PPS in the aerospace industry is for joint components in polymer composites. Since airplane structures are complicated which is not able to prepare in an individual process, polyphenylene sulfide -based composite materials are frequently used. Koutras et al. tested welded PPS joints reinforced with glass fibers in a range of temperatures. According to this study, when temperature rise, the lap shear strength dropped.

5.5 Behavior under compression

Wang et al. [45] conducted research on the compressive properties of PPS thermoplastic laminates made of carbon woven-ply, both with and without notches, at varying temperatures. According to the findings, the notched specimen’s stress-strain pattern and the unnotched samples at room temperature were similar. At higher temperatures, nonlinearity was also observed for the notched specimen, and this was linked to the matrix being softer. As can be observed in the matrix and interface, the notched specimens at 95°C and room temperature exhibited cracks that were comparable to those of the unnotched specimens. After determining that there was a clear delamination at room temperature and a shift in failure modes from wedge shear failure, they came to the conclusion that in the opposite scenario, elevated temperatures resulted in kink bands or even microbuckling.

Maaroufietal et al. [45] examined woven-ply PPS laminates; The authors of similar investigations came to the conclusion that the mechanism explained why further delamination resulted under compressive loading. Specifically, microbuckling in woven-ply misaligned structures was discovered to be caused by localized bending at the crimp. Moreover, in very ductile matrix systems, microbuckling coexisted with matrix plastic deformation, producing plastic buckling, or deformed inclined kink bands. Moreover, dispersing different carbon-based fillers, such as GNPs, pitch-based carbon fibers, and multiwalled carbon nanotubes, throughout the study by Khan et al. [46] on the impact of micro- and nanosized carbon fillers on the thermal characteristics of PPS composites suggests that the compressive modulus of the material can be tailored using the PPS matrix. Furthermore, the impact of carbon-based filler on PPS composites glass transition temperature (Tg) was investigated. The inclusion of filler particles, both micro and nanosized, can cause the Tg of the composites to increase by impeding the mobility of the polymer chains.

5.6 Behaviour under fatigue

Fatigue Behavior of previous research has delved into the topic of tiredness behaviors. Zhou et al. [47] examined the fatigue behavior of a material made with PPS. They discovered that the stress versus the number of cycles they created showed a significant shift in trend at the highest cycle stress to explore the interlaminar behavior of a PPS reinforced with five harnesses of carbon fabric. When quasi-static, hysteresis, and fatigue loading circumstances were taken into consideration, their results showed that no fractures formed under quasi-static loading, either until failure or with continuous loading and unloading with an increasing maximum load. Nevertheless, fatigue loading started to show flaws after fatigue life started. Reference [48] analyzed two different welding processes in earlier studies. One-sided welding provided inconsistent results that varied across the three specimens from a single cycle and between other welding cycles under the same conditions. Nonetheless, two-sided welding produced consistent findings, both within and between welding cycles.

A study was conducted on the fatigue characteristics as well as microstructure of PPS reinforced with carbon fiber fabric under conditions of extreme high cycle fatigue. The researchers also thoroughly analyzed the behavior of CF-PPS, a type of PPS reinforced with a carbon fiber twill 2/2 fabric, under extreme high cycle fatigue conditions up to 109 loading cycles. Results showed that as the stress ratio shifted between R = 0.21 and 0.51, there was a significant decrease in the allowable stress amplitude in the region of 106 to 109 cycles, which followed an exponential pattern. It was also defined as a preventive interval in which there was a 95% probability that any subsequent investigations' specimen failure would materialize. Furthermore, Mandell et al [49] investigated how the environment affected glass-reinforced PPS composites. They showed that at temperatures much over the glass transition temperature this material exhibited outstanding mechanical characteristics. It was found that the fatigue characteristics of glass and carbon fiber reinforced engineered thermoplastic polymers remained intact following exposure to heated air and water. There was no sign of a fatigue limit up to 106 cycles in the S-N curve that represented the fatigue behavior of these materials. However the PPS composite reinforced with glass underwent degradation, but the carbon-reinforced materials with a brittle matrix underwent degradation more slowly than those with a ductile matrix.

The uniaxial tension-tension mode tests were carried out at room temperature, with a minimum and maximum stress of 0.1. The authors of this study also produced S-N curves for several injection-molded thermoplastics and the glass or carbon-filled composites they utilized. The PPS composites failed because of crack propagation, and no fatigue limit was found in any of the thermoplastic matrix composites tested up to 106. Furthermore, for 40% glass fiber/PPS composites, a study by Oya et al. [50] found that the fatigue strength gradually declined with the number of loaded applications at 23 °C.

6. Summary

- This review emphasize the interconnectedness of physicochemical and mechanical properties in materials research, particularly emphasizing the significance of such a combined approach for materials like PPS (Polyphenylene Sulfide) that find extensive use in high-temperature applications across various industries.
- PPS's widespread utilization in diverse sectors, including automotive, coatings, electronics, and composite materials, underscores its remarkable properties and versatility. Even said, there are still a lot of unanswered questions, particularly when it comes to the long-term impacts of thermal aging in demanding workplaces and fatigue situations
- Furthermore is emphasized that additional research on PPS-based composites' fatigue characteristics is essential to improving their applicability for structural applications. Moreover, it is believed that understanding the behavior of PPS-based composites over time requires a complete understanding of their mechanical deterioration.
- The review suggests that there are ample opportunities for researchers to delve deeper into various aspects of PPS, both from a scientific and engineering standpoint. By addressing these knowledge gaps, researchers can not only enhance their understanding of PPS materials but also expand their practical applications in real-world scenarios.

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