Review Paper

Applications of polyimide coatings: a review

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Abstract
Polyimides, high-performance polymers with superior properties such as high temperature stability, resistance to solvents and high strength, can be used in high-tech applications of the aerospace and aviation, medical or electronics industry in different forms (film, fiber, nanofiber, membrane, foam, adhesive or coating). Among these applications, coating has a special place and is used to develop advanced structures having high temperature resistance, flame retardancy and etc. for high tech industries via an economical and feasible way. Therefore, in this review, we aimed to report the broad application status of polyimide coatings by reviewing publications, patents and commercial products. Thus, this study can assist in selecting suitable polyimide types and production methods for polyimide coating applications and in understanding their applicability for future products.

Keywords Polyimide · Poly(amic acid) · Coating · Optical fiber · High temperature resistant · Electrical insulation · Anticorrosion

1 Introduction

Polyimide (PI) is a high performance polymer that has superior properties such as temperature stability, resistance to solvents and mechanical strength. Due to their superior properties, PIs are used in different forms such as film, fiber, nanofiber, membrane, foam, adhesive or coating in high technology applications such as aerospace industry, medical and electronic devices, sensors [1–3]. PI films are used as thermal control coatings and also a protective layer for electronic devices and space applications thanks to remarkable optical properties (transparency and low solar absorption and infrared emission), high thermal stability and wide service temperature (− 300– + 300 °C), radiation resistance, enhanced electrical insulation (dielectric constant 3.4- 3.5), low density, toughness, flexibility, and high mechanical stability [4–11].

PI thin films are preferable for coating applications due to adhesion and transparency properties [12]. Especially coating applications are important because this is an economical way to obtain functional material, since the cost of the material decreases by using low amount of polymer. On the other hand, it is possible to provide high–value added material by an easy and economical process.

In the literature, there are numerous studies about different forms of PIs [13]. PI coating applications have attracted attention by researchers and manufacturers from past to present. Although there have been many reviews about PI chemistry [1, 14–19] or applications of PI materials [4, 20–24], no studies focusing on coating applications of PIs have been found. Readers can easily find information on PI coatings in this review and the cited sources. In this paper, by reviewing the studies in the literature on PI coatings and the patents reported on commercial products, the properties of the polyimides are explained in the first part, then the coating methods are explained and the application areas are given in detail in the last section.

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2 Properties of polyimides

High temperature resistance, mechanical and chemical stability, high glass-transition temperature (Tg), optical transmittance, low dielectric constant properties are characteristic for PI materials [18]. All of the mentioned properties of PIs can vary depending on chemical structure and macromolecular conditions such as molecular weight (MW), crystallinity or intermolecular forces [1, 25].

Thermal resistance is one of the most important property of the PIs. Highly rigid aromatic units provide thermal resistance to the polymer due to high Tg (> 300 °C) and decomposition temperature (500–600 °C) [8, 15, 26, 27]. Thermal oxidation resistance and high limiting oxygen index (LOI: 37–45) value of PIs originated from already oxidized structure of imide and ether linkages, moreover, increasing MW increases the oxidation resistance of polymers [1, 8]. Besides, PIs have high char amount (appr. 60%) and low heat conductivity (0.12 W/m.K) [26].

Besides rigid aromatic structure, dipole–dipole interactions between carbonyl bonds in the imide structure of macromolecules and charge transfer increases the Tg, mechanical and chemical stability of PIs. Amorphous morphology, flexible linkages in the macromolecule (such as ether) gives the elongation property to the PIs [1]. Highly aromatic structure and strong intermolecular interactions result low solubility and non-melting structure [16]. Adhesion of PIs on different substrates have been attributed to polar and non-polar functional groups in the structure [12, 13, 28, 29]. Since the synthesis of new types of PIs (low-melt PI, soluble PI, thermoplastic PI, colorless PI etc.) and the development of new coating methods, disadvantages of PIs are overcome by the researchers, the application area of PI coatings is expanding day by day.

First aromatic PI was synthesized by Marston Bogert in 1908 [30].Then at 1965, first commercial PI film was produced by DuPont named as Kapton [13]. Generally, aromatic PI is produced by two step method: First step is polyamic acid (PAA) synthesis from dianhydride and diamine monomers through exothermic polycondensation reaction in a dipolar solvent (N, N dimethyl acetamide (DMAC), N, N dimethyl formamide (DMF), N-methylpyrollidone (NMP) etc.) and second step is imidization reaction which is applied after solvent elimination from PAA as seen in Fig. 1. [18, 31, 32]. Commonly used dianhydrides are pyromellitic dianhydride (PMDA), benzophenone-3,3′,4,4′-tetracarboxylic dianhydride (BTDA) and 1,2,4,5-benzenetetracarboxylic dianhydride due to their high electron affinities ($E_{a,\ PMDA} = 1.90$ eV, $E_{a,\ BTDA} = 1.55$ eV. On the other hand, phenylene diamine and 4,4′-oxydianiline (ODA) structures with high basicity (pKa = 6.08) are preferred because of their high reactivity. Since PAA was synthesized with an equilibrium reaction, purity of the monomers is crucial to obtain high molecular weight PAA. Besides, while PAA forms amorphous random coils, rigid rod-like chain structures can be obtained with poly (amic ester) synthesized with diester diacid chloride and diamine. By mixing these two polymers, a polyimide fiber with high mechanical strength (462 MPa) and modulus (125 GPa) can be obtained. Moreover, it is possible to increase the solubility of polyimide precursor polymer in the non-polar solvents by synthesizing poly (amic silylester) with N,N′-bis(trialkylsilyl)diamines and aromatic dianhydrides at room temperature. During imidization reaction; while the ring closure reaction of the amic acid structures between 150 °C–400 °C, proceeds, the solubility and the Tg of polyimide increases [18, 31]. Two types of imidization treatment are applied as thermal and chemical imidization reactions. Gradual heating from 150 °C to 400 °C for a certain time is necessary to complete thermal imidization reaction [1, 13, 31, 33].

Chemical imidization is obtained by cyclodihydration reaction of PAA with acid anhydrides in dipolar aprotic solvents or tertiary diamine catalysts. In addition to the two-stage production method, there are many polymerization methods [13] for producing PIs such as;

1. One step method (solution polymerization and melt polymerization).
2. Diesters of tetracarboxylic acids (polyetherimide synthesis, PMR-15.)
3. Polyisoimides (lower Tg, more soluble and lower melt viscosity).
4. Ester derivatives of poly (amic acids) (storage stability, solubility).
5. Nucleophilic substitution reaction (poly (ether imides), lower Tg (200–280 °C), injection moldable, ULTEM 100 Thermoplastic Resin).
6. Exchange reaction (imidization without water molecule elimination).
7. Polymerization of dianhydrides and diisocyanates.
8. Cycloaddition reaction (Diels-Alders reaction of bismaleimides).
9. C–C coupling reaction.

In today's world where science and technology are rapidly developing, focusing on all the important features of polyimide instead of its limited characteristic properties can open up new perspectives and enable the development of new products. In this scope, polyamideimides and fluorinated PIs are other types of PIs that are developed to obtain the required properties for advanced. Commonly

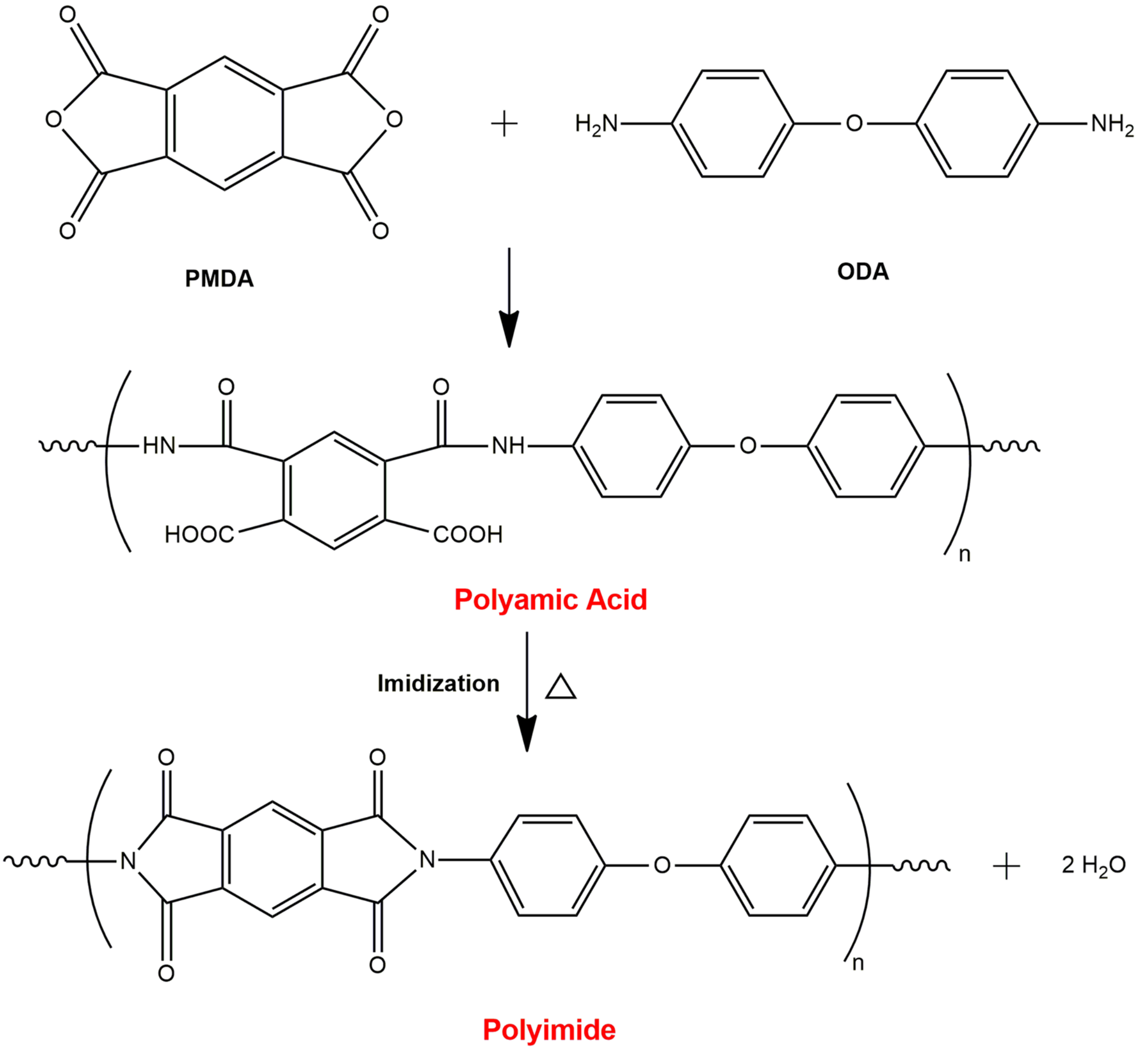


Fig. 1 Synthesis mechanism of Kapton [32]

used polyamideimide is thermoplastic PIs with enhanced mechanical strength, thermal and oxidative stability. Fluorinated PIs are developed for optoelectronics and solar cells requiring transparency or controllable light transmittance [13, 34, 35]. There are many other types of functional PIs varying according to used monomer such as photo-sensitive PI [36, 37], electrochromic PI [38], shape memory PI [39] or soluble PI [40, 41], thermoset or thermoplastic PI [42–45] and etc. The PI types, structures, properties, and uses were reviewed in Table 1.

3 Polyimide coating

PIs are suitable for coating applications due to adhesion to the several substrates such as metals, polymers, carbon, silica based materials (glass fiber, carbon fiber) etc. Soluble PAA precursor solutions or soluble PIs are suitable for several easy and cost-effective coating methods. It is possible to incorporate the superior properties that mentioned upper section of the PIs to the desired materials by coating method. Therefore, there are many applications related to PI coatings in both the literature and the industry. Sensors, spacecraft, electrical devices (batteries, displays, wires), medical devices, capillary tubes, separation membranes are some of these. Generally, aromatic PI-coated by two step method: First step is coating of polyamic acid solution on the substrate and second step is thermal or chemical imidization. [1, 13, 33]. There are several coating methods such as solution-coating, dip-coating [55], spin-coating [56, 57] or vapor deposition [58, 59], chemical deposition polymerization [47], and etc. Also new methods have been developed for PI coating on different substrates such as glow discharge vapour deposition polymerization, liquid flame spray method and etc. [60]. The coating process includes 4 steps (Fig. 2):

Table 1 Polyimide types, structure, properties and uses

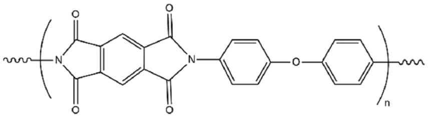
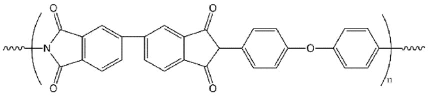
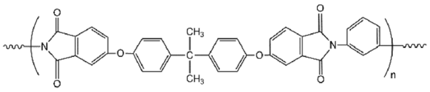
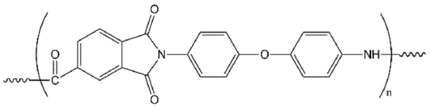
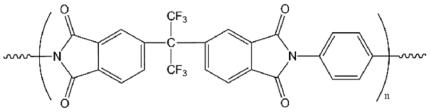
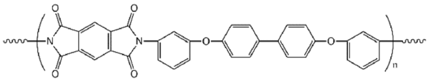
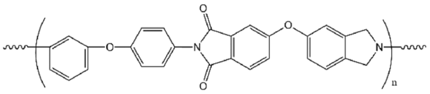
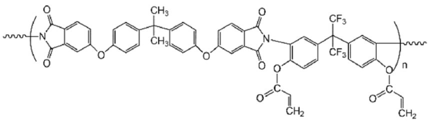
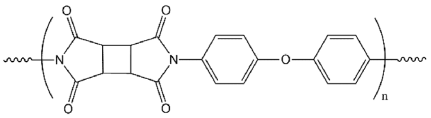
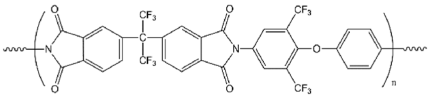
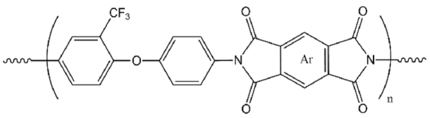
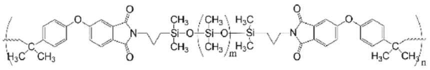
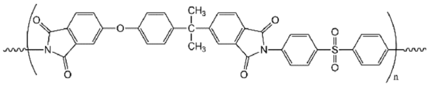
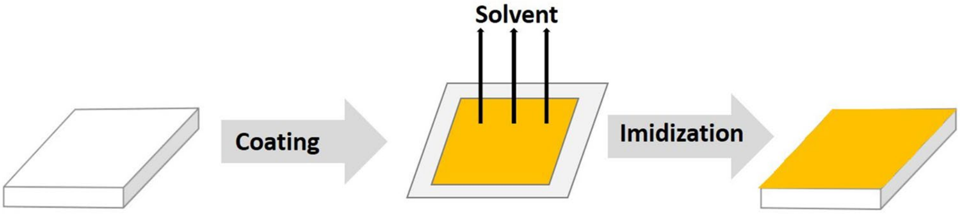
Type	Structure		Properties and Uses	Ref
Thermoset Polyimide (PI)		KAPTON® (PMDA + ODA)	Orange/yellow color No melting Non-soluble Thermal stability Chemical resistance Mechanical strength	[46]
		UPILEX® (BTDA + ODA)		
Thermoplastic Polyimide (TPI)		ULTEM® Polyetherimide (diacid anhydride + m-phenylene diamine)	Low temperature Tg Melting temperature Processable (molding, extrusion, and injection molding) Toughness, Damage tolerance, Repairable	[17, 47–49]
		TORLON® Polyamideimide (trimellitic anhydride chloride + ODA)		
		Avimid® N Fluorinated Polyimide n 2,2-bis(3,4-dicarboxy phenyl) hexafluoropropane dianhydride (6-FDA) + meta-phenylene diamine (m-PDA)		
		AURUM® (PMDA + 4,4- bis (3-aminophenoxy)biphenyl)		
		LaRC-IA® (4,4 -oxy-diphthalic anhydride (ODPA) + 3, 4′-oxybisbenzenamine (3, 4′-ODA))		
Photo-Sensitive PI		4,4′-(4,4′-isopropylidenediphenoxy)bis(phthalic anhydride) (BPADA) + 2,2-bis (3-amino-4-hydroxyphenyl)-hexafluoropropane (APAF)	Patternable via photo lithographic technique, Optical transmittance (> 85% in the visible light region), Packaging, insulating in microelectronics	[19, 50–52]
Colorless PI		Cyclobutane tetracarboxylic dianhydride (CBDA) + ODA		
		6FDA + 4-(4′-Aminophenoxy)-3,5-bis(trifluoromethyl)aniline		
Soluble PI		2-Trifluoromethyl-4,4′-diaminodiphenyl Ether + dianhydride (PMDA, BPDA, BTDA, and ODPA)	Soluble in organic or ionic solvents, Flexible displays, space applications	[40, 53, 54]
		Poly(imide siloxane)		
		EXTEM® Poly(ether imide sulphone)		

Fig. 2 Polyimide coating steps



1. Substrate preparation which is elimination of impurities on the substrate surface,
2. PAA solution deposition on the substrate by mentioned methods,
3. Drying process which is removing of the solvent (> 150 °C),
4. Curing step which is completion of imidization reaction (150–400 °C) [13, 31].

The quality of the coating depends on production parameters and conditions, such as coating methods, drying rate and temperature, heating rate and temperature of the imidization step. The coating method and thickness affect the molecular orientation and residual stress that causes crack damages. For example, since the thickness of PI coating layer which was produced with solution casting method is higher than that of coated with spin-coating method, the residual stress of solution casted PI is lower than that of spin coated [61]. Moreover, fast evaporation of the solvent causes the thermal shrinkage. Also, the heating rate for initial and final temperatures affect the morphology of the final coating. It is possible to decrease the thermal stress by controlled and gradual heating during the imidization step [13].

4 Applications of polyimide coatings

PI coating onto the different substrates (metal, polimer, carbon, glass fiber etc.) provides vast opportunity to be used in wide range of applications such as sensors, electronic devices, medical analysis devices, industrial machines or buildings etc. In this section, common applications of PI coatings were reviewed.

4.1 Sensor applications

Optical fibers are small diameter glass fibers that widely used for telecommunication applications but recent years mostly preferred in sensing applications. Optical fibers are used in sensors, instrumental analysis devices in chemistry, diagnosis devices in the medical industry or laser systems. These fibers conduct very critical missions, so mechanical durability and functional lifetime are important for embedded optical fibers. Moreover, the repairing process is almost impossible. Also, adherence to the embedded material and resistance to process conditions are crucial. For example, optical fibers which embedded in the epoxy matrix must stand 150–200 °C curing temperature and must adhere to the epoxy matrix [62]. Commercial optical fibers consist core and central layers which are made of different glass types. Central glass layer called the cladding which is coated with acrylate resin that resistant up to 100–110 °C which is not enough for many applications. Therefore, the cladding is coated with very thin PI film (5–10 μm) to provide high temperature resistance up to 400 °C and also mechanical strength such as high modulus, abrasion and static-fatique resistance [61–68]. Several patents have been focused on the improvement of PI coating for optical fiber protection. Polyimide-silicone block copolymers were developed to obtain better adhesion due to structural similarity with glass cladding and silicone groups [69]. Soluble-photocurable PI coating was developed to eliminate disadvantages of thermal imidization process such as water formation, and removal of residual solvent at high temperatures [67]. A new useful PI coating method was patented, low-temperature curing fluorinated-PI is coated during optical fiber drawing process occur to inhibit deterioration of optical fiber properties during coating and curing processes [68]. Dual PI coating method was developed to improve adhesion and provide elasticity, heat and moisture resistancy of optical fiber [70]. Strippable PI that can be easily stripped from the optical fiber with common, inexpensive solvents such as acetone was patented [71].

PI coatings are used to obtain sensor systems besides protecting against to working conditions [18]. It is not possible to produce humidity sensor from bare silica fibers since silica material is not sensitive to humidity. On the other hand, moisture sensitive PIs are hygroscopic and they show swelling when the water molecules diffuse, the swelling of the PI coating generates strain effect on the fiber. That behavior changes the Bragg condition of the Bragg grating optical fiber (FBG) and thus, provides the measurement of the relative humidity [18, 72]. By using this property of PIs, several studies were reported in the literature [72–78] (Fig. 3). For example, Kronenberg et al. studied the effect PI coating on the sensing ability of the

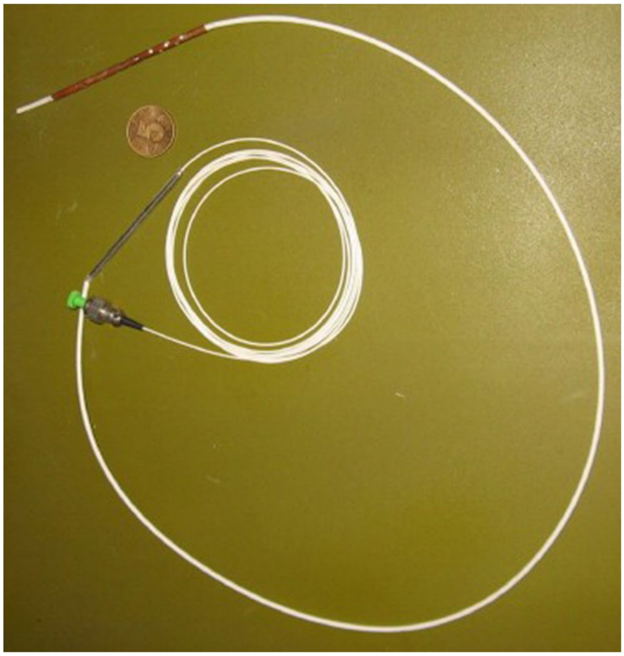


Fig. 3 PI coated RH Sensor [72]

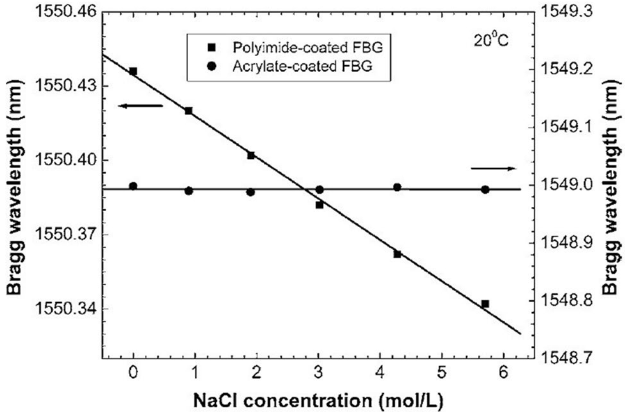


Fig. 4 Bragg wavelengths of acrylate- and polyimide-coated FBGs as functions of NaCl concentrations [85]

FBGs used for intrinsic relative humidity (RH) and temperature sensor. They have produced sensors that are sensitive to temperature and relative humidity ranges from 13 to 60 °C and from 10 to 90% RH, respectively. Also, they reported that the sensitivity of the sensor increases with an increase in the PI coating thickness (from 3.6 to 29 µm) [73]. A new micro-capacitive-type relative humidity sensor with nano-grass PI was developed as a dielectric sensing material [79, 80]. PI is coated on the top of the sensor system. Then PI film was etched in an O_2 plasma to obtain nano-grass surface. A nano-grass humidity sensor with high-performance properties was developed compared to a normal flat film type humidity sensor. Increased surface area and water affinity demonstrated a clear improvement over the normal flat-film sensor in key specifications such as quick response and sensitivity, low hysteresis, and long-term stability [79]. Besides, Yan et al. developed a soil moisture sensor with Bragg grating fiber by the help of the water sensitivity and linear expansion coefficient properties of PI layer. The designed sensor has the moisture measuring range between 15%RH ~ 75%RH, 12.6 pm/%RH senstivity and ± 10.26% accuracy [81].

PI coated optical fibers were also developed to measure fluidic properties [82–84]. Nellen et al. presented a PI-coated FBG that measure fluid pressure and temperature in the oil-bore holes. The stability to downhole conditions and lifetime were studied with modelling and accelerated mechanical and thermal aging tests. The obtained results show that PI coated sensor withstand 230 °C annealing temperature and also when used at lower than 1 GPa constant stress, the lifetime could be over 5 years [82]. Diamandi et al. coated with a new PI layer that transmit acoustic waves from the fiber cladding toward outside media while provides mechanical protection. Developed PI-coated optical fibers properly distinguish the air, ethanol and water over 100 m outside the fiber contrary to traditional optical fibers that could sense to liquids contact to the fiber [83]. Also, Chow et al. show the feasibility of the thin PI (8 µm) coated optical fiber for measure the acoustic impedances of the surrounding liquids [84].

The salinity degree is crucial for production control systems or ecosystem protection. Several sensor systems have been using to measure salinity. Conventionally salinity degree is determined by measuring optical refractive index with refractometer. Although refractometer used widely, they have some disadvantages such as low sensitivity and difficult measuring due to bulky system. Optical fiber sensors have many advantages such as small size, low cost, higher sensitivity, and ability of getting response over a long distance [85]. Therefore, optical fiber sensors are preferred instead of refractometers as salinity sensors. PI coating on the optical fiber not only protect against the breakage but also, provide salinity sensing property [85]. There are several studies about development of PI coated FBG sensors for measuring salinity and temperature [85–88]. For example, Men et al. have fabricated a multiplexed PI coated fiber Bragg grating sensor for simultaneous salinity and temperature measurement. Developed sensor was compared with acrylate coated FBG sensor. The developed sensor system showed that the PI-coated grating responds to variations of both temperature and salinity, while the acrylate-coated grating is only sensitive to the environmental temperature (Fig. 4). The experimental results indicated that the temperature and the salinity sensitivities of the PI-coated grating were 0.0094 nm/ °C and 0.0165 nm/M, respectively [85].

PI coated membranes can be used as a gas sensor. For example, Aslam et al. have fabricated a PI membrane for low loss microheated metal oxide (MOS) gas sensor. Generally, silicon oxide or silicon nitride used to produce this type of membranes. But the fragility of these materials reduces the yield and dielectric thickness and active area. They used thin rugged PI membrane to reduce the power consumption of a metal oxide gas sensor due to high elongation modulus and easy control layer thickness. Liquid PI (DuPont PI2575) was spin-coated on bulk micromachined silicon wafer then cured at 400 °C for 30 min. Then Pt heating elements were added to the gas sensor system. Temperature resistance tests show that PI coated heater withstand the 300 °C temperature that needed to activate the sensing layer for certain gas detection. PI is a better thermal insulator and easy to deposition Pt on PI layer due to the smoother surface and adhesion property compared to oxide or nitride membranes, therefore, polyimide preferred to produce low power sensor over an oxide or nitride membranes [89]. Similar studies have been reported in the literature [90, 91]. Flow cell test results indicate that PI-coated sensors inhibit the effect of gases, such as carbon monoxide, acetylene, ethylene, and methane on the H_2 response, dramatically improving selectivity to hydrogen compared to un-coated palladium MIS sensor (Pd-MIS) device [92]. Recently, different sensors were developed for thermal-strain sensing of rails. Two types of jacketed fibers and a carbon/polyimide coated single-mode optical fiber were used in the sytem to observe jacket effect on the thermal-strain sensing in the rail [93]. On the other hand, new studies show that it is possible to improve sensor response time and stability by addition of polar groups (-COOH, -OH) to the PI structure that coated on the FBG [94]. The studies about this area continue to improve sensor sensitivity and coating quality and also to develop new sensor types.

4.2 Electronic device and battery applications

Electronic displays show thermal shrinkage problem under working conditions [95]. Introducing the PIs as micro-electric coatings enhances mechanical strength and also thermal stability [96]. PIs are very proper polymers for electronic applications due to superior dielectric properties such as high electrical insulation (dielectric constant 3.4–3.5) [5–8], high ductility (ultimate elongation, 72%) [8] and low thermal expansion coefficient (CTE, 20 ppm/°C) [8, 97]. Thus, in the literature, many studies have been reported about PI coated electronic devices [98].

New polyimide-clay nanocomposite films as protective coatings were developed to protect microelectronic devices. PAA-clay nanocomposite coating solutions were prepared [99], and then, coated on a silicon wafer and glass substrate. Finally, thermal imidization at 300 °C for 2 h was performed. Obtained PI-clay coating is suitable for protective coatings in the microelectronic area due to adhesion property to silicon substrate, besides high resistivity, low CTE, and low O_2 permeability and water absorption, also high mechanical and dielectric strength [100]. PI aerogel coated carbon nanotube data and power cables (Fig. 5) can be produced with carbon nanotube yarn used as conductor instead of copper wire to decrease the weight in aerospace and automotive applications and PI aerogel (foam) coated with impregnation and rollers, as light-weight dielectric insulation layer. PI aerogels were synthesized with poly (isobutylene-alt-maleic anhydride), poly(isobutylene-alt-maleic anhydride) (PMA-D) crosslinker, 4,4′-bis (4-aminophenoxy) biphenyl (BAPB) and biphenyl-3,3′,4,4′- tetracarboxylic dianydride (BPDA) monomers via chemical imidization [101]. In another study, double walled CNT (DWCNT) wires and cables were produced via chemical dip coating method. The wire consists of DWCNT coated polytetrafluoroethylene (PTFE) core and PI insulation layer. Iodine treated wire has low resistivity value as 4.5 10^{-6} Ω. m. [102].

Although the microfibrillated cellulose (MFC) sheets as biodegradable product can be used in microelectronic

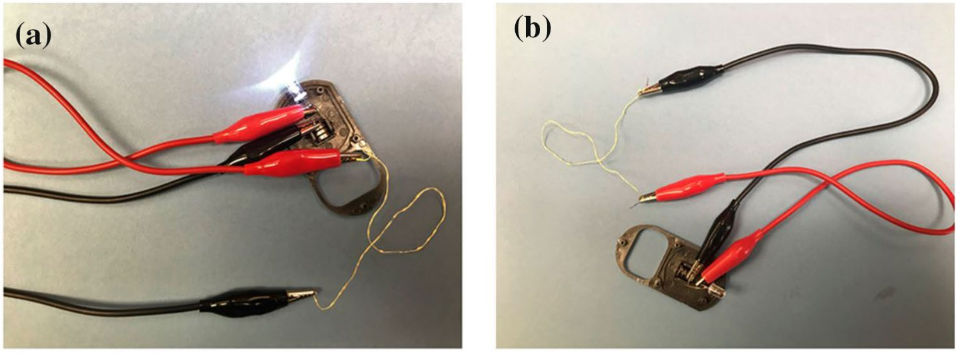


Fig. 5 The images of a) LED light turns on when the clips were connected with the CNT yarns. b) LED light turns off when the clips were connected on the polyimide aerogel coatings. Reprinted with permission from [101]. Copyright 2019 American Chemical Society

industry, MFC sheets have high surface roughness, poor dielectric properties and also, porous and hydrophilic structure which are not desired for electronic devices. Therefore, a thin PI coating on both surfaces of MFC sheets can be incorporated to improve dielectric properties for flexible substrate of an electrostatically actuated mechanical switch device. Relative permittivity was decreased from ~ 10–70 to ~ 3–6 [103].

There are several studies about PI coatings used in optoelectronic devices. Organic light emitting diode (OLED) displays consist an insulation layer which require certain properties. These are photosensitivity for patterning process, curability less than 250 °C temperature, high and stable dielectric strength, thermal stability, adhesion to various substrates. A positive-tone photosensitive PI coating was developed as an insulation layer for OLED displays and compared with novalac resin and acrylic resin. After imidization at 230 °C for 30 min, O_2 plasma treatments (durable to this treatment no loss of film thickness after 20 min) were applied to the novel coating showed better thermal (no outgas (weight loss) until 320 °C) and electrical properties (350 kV/mm after 20 days at 85 °C) and also, better adhesion (no peel off more than 500 h at 121 °C 2×10^5 Pa, 100% relative humidity) on substrates (glass, ITO and SiO_2) compared to other coating polymers. Light emiting durability tests (voltage were applied at 80 °C for 72 h) were conducted to coated OLED displays, novel PI coated OLED display did not show pixel shrinkage while novalac and acrylic resin coatings showed 64% and 47% pixel shrinkage, respectively [104]. Moreover, Chien et al. produced high response time (3.4 ms at 5.5 V) liquid crystal displays (LCD) with optically compensated bend (OCB) cells method. They used ion-beamed PI layers to obtain lower warm up (transition) and response time. Ar^+ ion beam treatment increased the nucleation sites in the surface of PI, thus the transition time reduced from 24 to 17 s without morphological destruction. [105]. Nakano et al. developed flexible active matrix organic light emitting diode (AMOLED) displays. PI film was coated on a glass substrate with a process that is compatible with mass-production lines and than amorphous In–Ga–Zn–O thin-film transistors (a-IGZO TFTs) coated on transparent PI films. Finally glass substate was removed from PI film. The results show that a-IGZO TFTs on PI film stable to annealing process at high temperature (up to 290 °C) [106]. Also, French et al. have developed the thinnest PI-based plastic display with a five-micron plastic substrate for the thin-film transistor (TFT) array (Fig. 6) by electronics on plastic by laser release (EPLaR) process [107].

Researchers reported molecular dynamics simulation studies to show the interfacial adhesion mechanism of PI to the silica glass for production of flexible displays. Adhesion depends on hydroxylation degree on silica glass surface, crystallinity of silica glass, and oxygen density within PI structure. Adhesion occurs via hydrogen bonding between oxygen atoms in PI and hydroxyl groups on the glass (Fig. 7a). Moreover, surface roughness increased the surface area so, more hydroxyl groups reveal and adhesion energy increases (Fig. 7b). also crystallinity of silica decreases the adhesion due to decreasing the roughness of silica surface [108–110].

Fig. 6 50 × 50 mm a-Si TFT array on 3 μm thick freestanding polyimide layer made by the EPLaR process [107]

Numerous patents focused on PI coating on displays for different purposes. An aqueous alkali-developable photosensitive PI precursor resin was invented for the purpose of use as highly heat-resistant transparent protection layers and insulation layers for LCD devices [111]. A new method was developed for polyimide coating on LCD panel to improve coating parameters such as cost time, quality [112]. Multi-layered PI cover film production containing optical adhesive layer with nanoscale colorant to inhibit characteristic yellow colour of the polyimide for the flexible display panel [113], soluble PI synthesis and coating for flexible displays [114] and an OLED device production with longer service life with PI base layer that improved the water and oxygen blocking performance [115] were presented as patent.

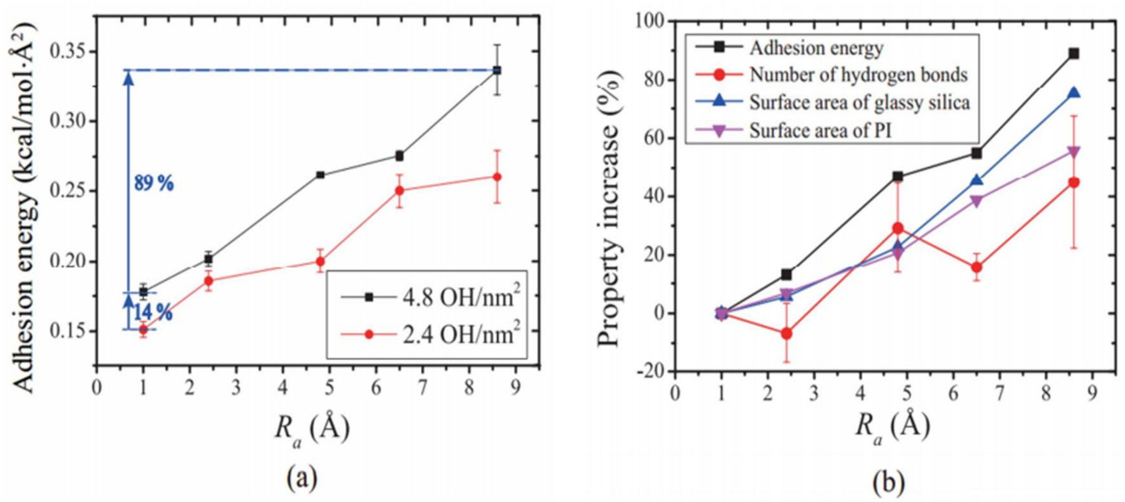


Fig. 7 Adhesion energy as a a function of average roughness (Ra) (1.0 ~ 8.4 Å) and hydroxylation density (2.4 and 4.8 OH/nm^2) (a), Adhesion energy, number of hydrogen bonds, surface area of glassy silica and PI increment (%) as a function of Ra (1.0 ~ 8.4 Å) Reprinted with permission from [109]. Copyright (2017) American Chemical Society

The PI coatings are also used to improve the mechanical strength and thermal shrinkage resistance in batteries. Thermal shrinkage of polyethylene separators is a crucial problem for lithium-ion batteries. Soluble co-polyimide (P84, random co-polyimides composed of 3,3′,4,4′-benzophenone tetracarboxylic dianhydride (BTDA) with 80% toluene diisocyanate (TDI) and 20% methylene diphenyl diisocyanate (MDI)) was synthesized and coated on a PE separator with a dip-coating method. Optimum coating concentration was determined as 3% (wt polymer/wt DMF) and thickness is 23 µm. Heat exposure test at 140 °C, 30 min showed that the PI coating improved thermal shrinkage resistance (no shrinkage) while preserving electrochemical properties (Fig. 8) (ionic conductivity $2.43 \times 10-4\ \mathrm{S\ cm^{-1}}$ similar to bare PE ($2.54 \times 10-4\ \mathrm{S\ cm^{-1}}$), (electrolyte resistance up to 4 V) of the battery due to high thermal resistance of PI and the proper porous structure. Thermal resistance property was evaluated by open circuit voltage (OCV) measurement. PI coated battery resist (OCV value 4 V) 140 °C for 110 min while OCV value of the bare PE drop 0 °C after 60 min [95].

Also, PI aerogel-polyethylene double-layer composite seperators which are temperature resistant up to 140 °C and do not show thermal shrinkage contrary to commercial PE seperators, provide safe usage conditions against explosion and overcharging for high-safety lithium-ion batteries. Besides, coin cells with PI aerogel/PE separator show similar cycling and higher C-rate performances with PE seperator due to high electrolyte uptake (246% for aerogel/PE while 136,5% for PE seperator) and wettability

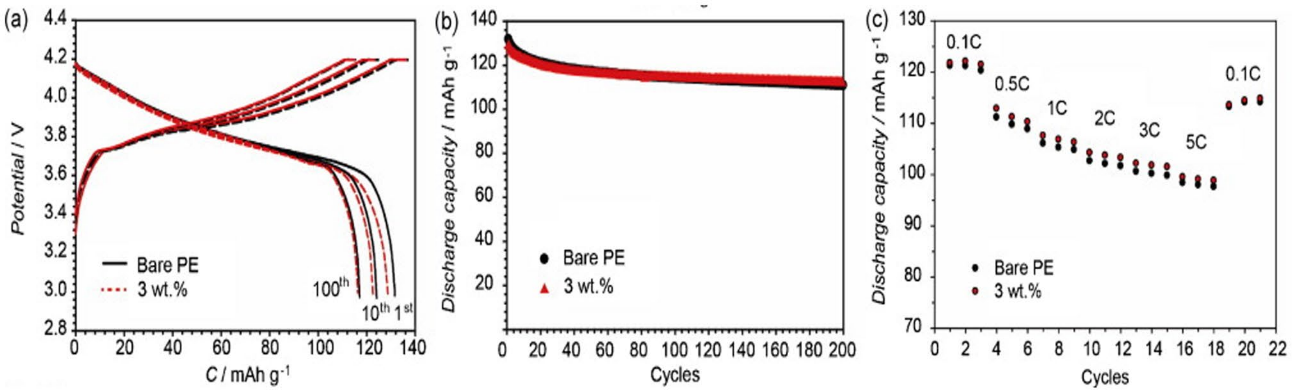


Fig. 8 Charge–discharge profiles (**a**), cycling performance (**b**), rate capability (**c**) of the unit cells employing the bare PE separator and the 3 wt.% P84-coated PE separator [95]

of seperator with electrolyte [116]. Lithium-ion batteries are used for portable electronics and electrical vehicles. Especially the spinel lithium titanate ($Li_4Ti_5O_{12}$, LTO) material is one of the most effective anodes for long-life and high power lithium-ion batteries. However, LTO anodes cause interfacial side reactions during charge–discharge and storage, this problem limits the wide usage lithium-ion batteries. This problem can be solved by incorporating an ion conductive PI layer on the $Li_4Ti_5O_{12}$ anode material. First, PAA precursor solution (PMDA-ODA) was synthesized and coated on the anode material. PI gel electrolyte layer was obtained after thermal imidization. The thermal resistance, ion transport property, nano-scale thickness and full protection of surface inhibit the side reactions between the partially charged LTO and liquid electrolyte (Fig. 9). Thus, the cycling and rate performance of developed lithium-ion batteries were improved [117].

By coating carbon nanotube electrode with PI layer, side reactions between electrode and electrolyte can be prevented. Thus, the cyclic performance of long-cycle Li-air batteries was improved [118]. Similarly, Yoon et al. have coated PI on carbon nanotube and prepared air electrode material. Electrochemical test results show that PI coating suppresses unwanted side reactions [119]. In a recent study, PI spheres and poly(acrylonitrile) fibers were coated on the Cu substrate and Li metal deposited to simulate Li-ion battery working condition. The results show that dual coating layer inhibit dendrite formation on the Li metal layer that negatively affect the battery performance [120]. Recently, PI coating of lithium titanate particles to reduce gas formation in the electrochemical cells were patented [121] Electrode cracking is another serious problem of lithium-ion batteries that reduces the capacity. The crack-resistant and high performance batteries can be developed by high modulus–high compressive PI coating on SnO_2 electrode materials holding particles, in contact during charge and discharge. Moreover, the PI coating improves capacity retention and stable capacity of after 300 cycles [122]. On the other hand, silicon thin films have electrode cracking and delamination problems during cycling that causes capacity degradation. When silicon thin film electrodes capped with PI to solve mechanical degradation problem, PI layers protect the electrodes, so the battery could be used with a high

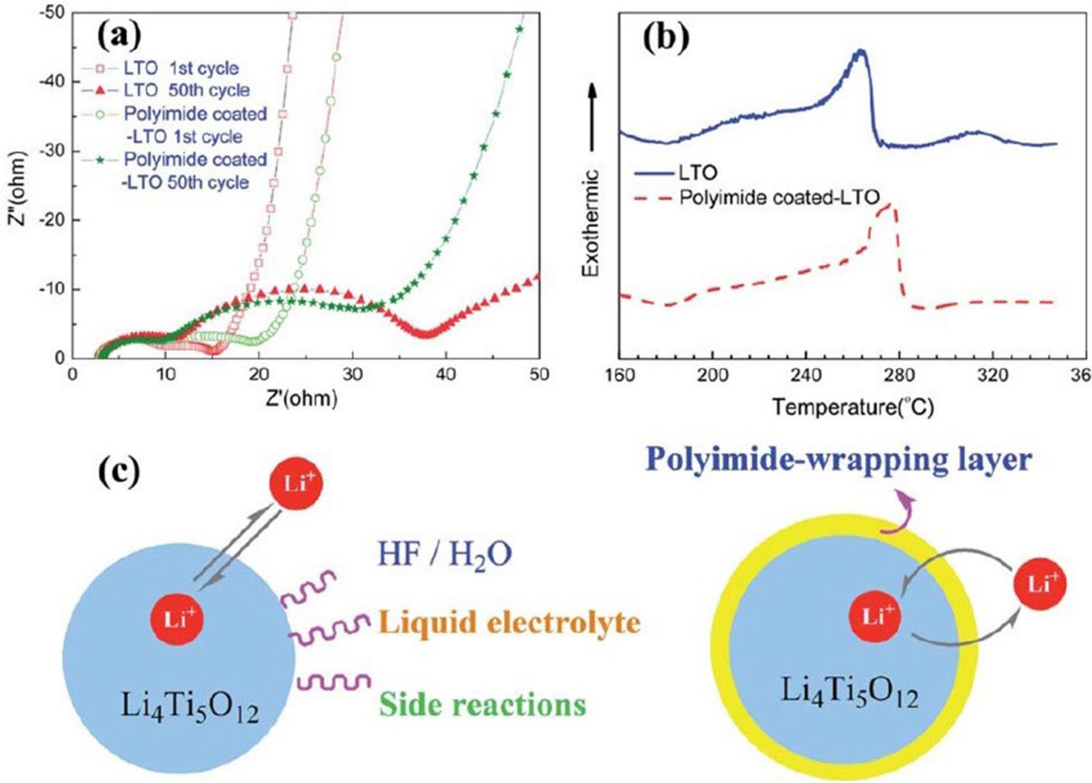


Fig. 9 **a** Variation in alternating current (AC) impedance spectra of cells assembled with pristine LTO and polyimide-coated LTO at 55 C; **b** DSC thermograms of the interfacial exothermic reaction between partially charged LTO and polyimide-coated LTO and liquid electrolyte; **c** schematic illustration of ion-conductive polyimide nanocoating layer for suppressing the interfacial side reactions. Reproduced from Ref. [117] with permission from The Royal Society of Chemistry

capacity of 2610 mAh g^{-1} at 100 mA g^{-1} up to 300 cycles without capacity loss at 3500 mA g^{-1} [123].

The hydrophilic PI changes the resonant frequencies of the antenna with atmospheric relative humidity, so relative humidity will be measured by detecting the resonant frequencies. Therefore, PI coated Yugi-Ada antennas can be designed and analyzed for humidity sensing application. Simulation results show that this system could be alternative to existing humidity sensors [124].

Moreover, there are patents about PI coating on electrodes for production of paterning layer [125] and photolithography application [126]. On the other hand, several patents were focused on electrical wires coated with PI layer for insulation. Electrical wires have been improved over time by using low-melt PI and PAA solution to easily (melting at low temperature) repair damaged electrical wires [127], easily coatable low viscosity insulating varnish (PI precursor solution) [128], low-dielectric constant PI insulation coating [129]. Also, implantable medical device cables (lead) for electrical stimulation coated with PI providing conductor coil insulation have been developed [130].

Additionally, advanced coatings showing better UV curing ability, optical transparency, thermal stability, hardness and lower moisture uptakes respect to conventional Kapton films can be synthesized about to be used LCD, photoelectric, microelectronic applications [126, 131–133].

4.3 Anticorrosion applications

Polymeric coatings inhibit corrosion by physically blocking diffusion of the species such as O_2 and H^+ [134]. NASA developed a new PI powder coating material for metal substrates such as pipes and other infrastructure components, machinery, exposed metal parts and structures, automobile components, bridges provides anti-corrosion property. PI coated metal was obtained by spray coating of the low melting point PAA and curing in powder coating oven [135, 136]. By incorporating the layered montmorillonite clay and coating organosoluble polyimide/clay nanocomposite material on the steel substrate, anticorrosion property was enhanced. Organosoluble polyimide/clay nanocomposite material show better corrosion resistance compared to polyaniline, poly(o-ethoxyaniline) and poly(methyl methacrylate) [134].

An electroactive PI (EPI), a promising anticorrosion material, was synthesized by reaction of amine-capped aniline trimers (1,4-phenylenediamine) and 4,4′-(4,4′-isopropylidenediphenoxy)- bis(phthalic anhydride) (BSAA) and then coated on steel as a thin layer (20 μm) show advanced corrosion inhibition [55]. Huang et al. obtained effective anticorrosion coating with synthesized aniline tetramer (AT) capped electroactive imide oligomer and a polymer with electrochromic properties [137, 138]. Corrosion resistance of EPIs can also be improved by incorporating TiO_2 nanoparticles to the coating solution. While EPI layer inhibits corrosion of cold-rolled steel (CRS) electrode by the formation of a protective passivation oxide layer, TiO_2 nanoparticles make complex the O_2 diffusion pathway (Fig. 10) [139].

Besides, incorporation of SnO_2 nanoparticles to the EPI coating improves thermal and anticorrosion properties of coating on the steel. The EPI/SnO_2 nanocomposites were prepared by in situ oxidative coupling polymerization of oligoaniline and thermal imidization processes. The EPI/SnO_2 nanocomposite was coated on 316L stainless steel and cold rolled steel with spin coating method. The semiconductor property of both SnO_2 and EPI provide synergistic effect against corrosion by redox reaction and also, SnO_2 nanoparticles form a barrier to inhibit corrosive ion transition. The anticorrosion property of low nickel stainless steel (AISI 201) can be improved by incorporating copper oxide (CuO) into the EPI by oxidative coupling polymerization followed by coating then thermal imidization [140, 141]. EPI was also synthesized to develop a biomimetic superhydrophobic surface for advanced anticorrosive coatings via nanocasting technique [142].

Beside the steel substrate, it is also possible to protect aluminum substrates by coating with polyimide [143]. Polyurea-b-polyimide (PUI) block copolymer that providing long lifetime (about 8 years), high contact angle (110°) and low surface energy (about 25.5 mJ/m^2) was synthesized

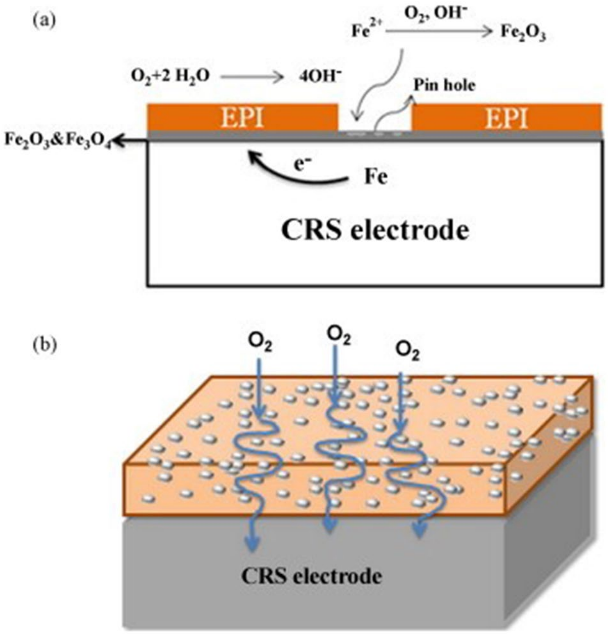


Fig. 10 Corrosion protection mechanism of the EPI (a) and TiO2 (b) layer on the steel [139]

and coated on aluminum alloy 2024-T3 [144]. When the structure and morphology of the PUI block copolymer coatings were investigated, intra– and inter– hydrogen bonding between PI and polyurea macromolecules were detected. This entangled morphology provides corrosion protection by reducing surface energy and providing barrier properties. Moreover, H-bonded imide chains avoid the hydrolysis of the ring structure in a corrosive aqueous environment [145]. Also, graphene-based PI coatings have been investigated. Chang et al. produced graphene/EPI nanocomposite coatings that have improved anticorrosion property over EPI coating on CRS electrodes. The results show that synergistic effect of redox catalytic property of EPI and oxygen barrier property of graphene nanosheets enhanced the anticorrosion effect [146]. In order to investigate the anticorrosion property of PI with alumina-covered graphene oxide, alumina-covered graphene oxide/polyimide (AlGO/PI) nanocomposite coating material was produced by sol–gel method. Anticorrosion behavior was improved by isolating charge transfer pathway by alumina on GO [147].

4.4 Capillary tubes

Capillary tubes used in column chromatography devices are very brittle and sensitive to high temperatures and lose their properties when using chemicals for a long time, thus reducing the reliability of the device. In practical applications, the capillary columns are coated with flexible polymers that exhibit thermal and dimensional stability, good adhesion, mechanical flexibility, toughness, hardness to winding and abrasion, as well as chemical resistance. PIs are one of the best candidates for a high performance coating material providing the desired properties. [148]. PI coating can be applied on fused silica-capillary tubes due to flexibility, high mechanical strength, and chemical inertness. PI coated fused silica tubes are used commercially for capillary electrophoresis, capillary electrochromatography and gas chromatography [149, 150]. Novel PI copolymer including benzimidazole groups in the structure to increase thermal stability and adhesion property of the coating was developed and coated to protect intrinsically brittle quartz chromatographic columns. As a result, while Tg increased to 346.9 °C, CTE decreased to $24.6 \times 10-6$/K in the range of 50–300 °C. Besides, the novel PI resist 100-cycle thermal shock test in the range of 25–320 °C without cracking, delamination, warpage, or other failures [148].

PI coated optical fibers or capillary tubes are suitable for medical applications such as sensors, laser surgery devices or diagnosis instruments [130, 151–153]. Resistance to cryogenic temperature beside high temperature is important for medical devices. Also, PIs are resistant to medical process conditions such as sterilization. On the other hand, PI coatings are inert and non-toxic, resistant to solvents and chemicals. Moreover, mechanical strength and flexibility properties of PIs make them good candidates for medical applications.

4.5 Membrane applications

Membranes are preferred for separation applications such as gas separation [154], water treatment [155], liquid pervaporation [156], and etc. thanks to porous structure. The thermal and chemical resistance of membranes can be enhanced by PI coating on the membrane structure [157, 158]. Moreover, PIs increase the selectivity of the membranes by adsorbing or interacting with species [159]. PI-coated composite membrane was obtained by dip coating of asymmetric polyimide membrane (as support) in PAA salt solution and imidization process. Firstly, PAA sodium salt solution was synthesized with PMDA and ODA, then mixed with trimethylamine to achieve chemical imidization. Developed PI coated composite membranes showed improved gas separation performance with the CO_2/N_2 selectivity of over 25 on gas permeation, and separation factor α (H_2O/EtOH) of over 800 with a total flux of 0.21 kg/m^2 h on pervaporation [157]. Also there are studies about development of PI coated composite membranes by the solvent-less vapour deposition followed by in-situ polymerization (SLIP) technique [160].

PI is preferred as sorbent layer due to pi–pi stacking interaction of PI with other organic compounds or adhesion of electronegative elements (N or O) of PI structure with inorganic compounds. Therefore, PI-coated magnetic nanoparticles can be produced as a sorbent in the solid-phase extraction of polycyclic aromatic hydrocarbons such as naphthalene, anthracene, and pyrene in seawater [159].

Additionally, gas separation PI membranes by PI coating on porous polysulphone hollow fibers provides maximum gas separation performance (the CO_2/CH_4 separation factor was 30.1, and CO_2 permeance was 5.7×10^{-5} cm^3 (STP)/ (cm^2/cm.Hg.s)) respected to non-coated polysulfone membranes (the CO_2/CH_4 separation factor is 13) [161]. Recent studies have been focused on polyimide membranes rather than PI coated membranes due to higher effectivity [162–165].

4.6 Polyimide coatings on high temperature resistant materials

PI coating is a very promising application for transfer the excellent properties of PIs to various materials. The studies also focused on PI coatings on high temperature resistant materials due to thermal imidization process. Researchers have studied the adhesion behavior, effects of PIs, and different effective coating methods on several types of materials such as steel, copper, aluminum or carbon fiber.

4.6.1 Metallic substrates

Copper materials are widely used in electronic devices due to low cost and high electrical (58.7 10^6 S/m) and thermal conductivity (386 W/m.K) [29]. Since copper materials are susceptible to oxidation upon exposure to high temperature or high humidity [166], protective coating to increase reliability and service life is required. In the literature, after synthesis of PMDA-ODA based PAA in NMP solvent and coating on Cu foil, imidization was performed by heating slowly from 150 °C to 400 °C and adhesion behavior between polyimide and copper was investigated. The high peeling strength which is desired for microelectronic devices was reported between copper and PI [29]. The PI was studied as a binder on Cu/AlO_3 film to improve adhesion between Cu wire and other substrates of stretchable and transparent heater. The developed Cu wire/alumina/polyimide-based transparent heater showing remarkable properties such as high temperature resistance (300 °C), high flexural strength by enduring 100 cycles of stretching releasing at a strain of 30% could find application in heating of future wearable optoelectronic devices [166]. The phosphinate diamine groups-contained PIs were synthesized that exhibit heat resistance, adhesion property and also, excellent hot-melt processability for flexible copper clad laminates [167].

Steel materials are often used in industrial applications, since they have high mechanical strength. However, those machine parts exposed to harsh conditions such as high friction, heat, or corrosive liquids. So, PI coating is one way to reduce these negative effects [168, 169]. The liquid flame spray method that does not require thermal imidization process was applied to obtain polyimide-copper (PI-Cu) coatings on a steel substrate. Newly developed PI-Cu coatings showing anti-fouling and anti-corrosion properties could be used in marine applications [170, 171]. PI coated stainless steel high loaded bearings can be produced by the wet coating method. When the lifetime of coated and non-coated bearings by friction test was compared, it was seen that the lifetime of uncoated bearings lasted 150 h, while PI coated bearings lasted 500 h. Moreover, PI coatings on steel surfaces may lower the overall consumption of lubricants due to decreasing of wear [172].

Tribological and wear properties can be improved by using polyimide/epoxy resin-polytetrafluoroethylene (PI/EP-PTFE) bonded solid lubricant coatings filled with silver nanoparticles. Better friction and anti-wear abilities of steel materials were obtained compared to coatings with RP-3 aviation kerosene (Fig. 11) [173].

In another study, PTFE and SiC filled PI composite coatings on aluminium substrates improved the mechanical and tribological properties. The results showed that the fillers lower the friction coefficient from 0.38% to 0.18%. However, wear rate decreased slightly and thermal degradation bahavior remained with same as pure PI coated material [27]. Cakir et al. developed PI nanocomposites that contain fluorine and SiO_2 particles (perfluorooctyltriethoxysilane and tetraethyl orthosilicate) with sol–gel method. The PI nanocomposite coatings with 5–10% reinforcement amount improved the hydrophobicity, wear and thermal resistance, adhesion, hardness and, methyl ethyl ketone solvent resistance [174]. Same group synthesized the new PI (PIF) with 6FDA (hexafluoroisopropylidene diphthalic anhydride) and/or NTDA (1,4,5,8

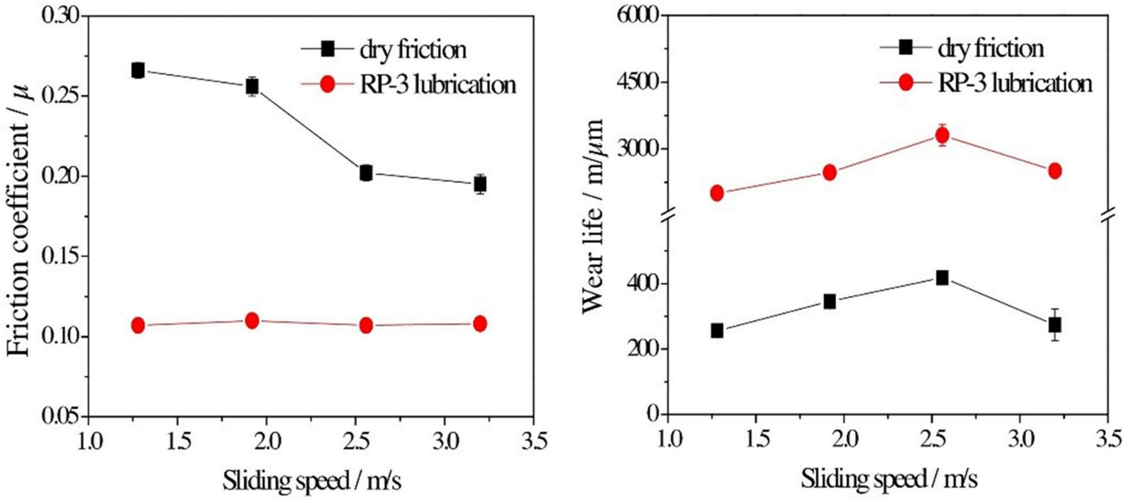


Fig. 11 Friction coefficient and wear life graphics of PI/EP-PTFE and Ag nanoparticles (RP-3 lubrication) coated steel [173]

naphthalenetetracarboxylic dianhydride) and terminated with 1H,1H-perfluorooctylamine (PFOA) (1% of the PI chains). Then, the PIF polymer was coated on aluminum substrates by using a 75-µm wire-wound applicator and thermal imidization was conducted. The test results reveal that the properties of the PIF coating improved the glass transition temperature, thermal stability, gloss value, abrasion resistance and, pendulum hardness value when compared with neat PI coating [175].

Recently, the tribological and thermo-degradation properties of steel materials were enhanced by carbon based nanoparticles such as multi-walled carbon nanotubes (MWCNT), graphene etc. filled PI coatings [176–178].

4.6.2 Carbon fiber

Carbon fibers are high performance fibers that consisted at least 92% carbon atoms. These fibers are produced from different precursors such as polyacrylonitrile fiber and pitch. The production steps are high temperature oxidation, carbonization and graphitization processes [179]. Carbon fibers have high specific strength and high modulus, so they are used to produce composite materials for in aerospace, automotive, and sporting goods [180]. PIs are one of the preferred organic matrices for hybrid coatings or nanocomposites due to high thermal resistance, mechanical strength, chemical inertness and also, adhesion properties. PI coatings are applied to the carbon fibers to enhance mechanical or thermal properties of the materials.

Naganuma et al. produced PI coated carbon fibers by high temperature vapor deposition polymerization (VDP) method and thermal imidization process. Two types of PI were synthesized which are PMDA and ODA-based that coated on carbon fiber and 3,4,3′,4′-benzophenone tetracarboxylic dianhydride (BTDA) and 4,4′-methylendianiline (MDA)-based that used as the matrix polymer. Mechanical tests showed that PI nano-coating (100 nm) improved the tensile strength (from 5.31 ± 0.29 to 5.76 ± 0.25 GPa) and Weibull modulus (from 20.8 to 25.1) of the T1000GB carbon fiber (Fig. 12) [180] Similar results were obtained in another study [181]. It was reported that PI coating on carbon fibers by especially VDP coating method heals the nano-flaws on the carbon fiber, since small-sized monomers and polymers penetrate into the nano-flaws [182]. Electrophoretic deposition technique which is more economical and environmental according to VDP method is also used to provide strong adhesion mechanism between PI and carbon fiber due to chemical bonding and increased decomposition temperature of carbon fiber (from 330 °C to 545 °C) indicating that the PI coating suppresses the oxidation of carbon fiber [183]. Organic solvent-free PI coating techniques with epoxy systems [184], photodegradation property of methylene orange [185], PI-silica hybrid colloidal composite coating which improves the thermal resistance of carbon fiber up to 600 °C [186] and sol–gel process for polyimide coating [187] were also studied.

4.6.3 Textiles

By coating the PI films on different textile materials, functional properties such as high heat resistance, flame retardant and chemical resistance can be gained. Hybrid membranes were produced by coating PI nanofibers onto Kevlar fabric for protection against heat and flame. First, organo-soluble PI was synthesized from 4,4′-(4,4′-isopropylidenediphenyl-1,1′-diyldioxy) dianiline and 4,4′-oxydiphthalic anhydride and then, obtained PI dissolved in DMF and deposited onto Kevlar fabric substrate by electrospinning method. [188]. Same technique was applied onto polyester fabrics [189]. The thermal and tensile properties of p-aramid yarns were improved by PI film coating by impregnation of PAA and imidization at high temperature. Lee et. al. coated

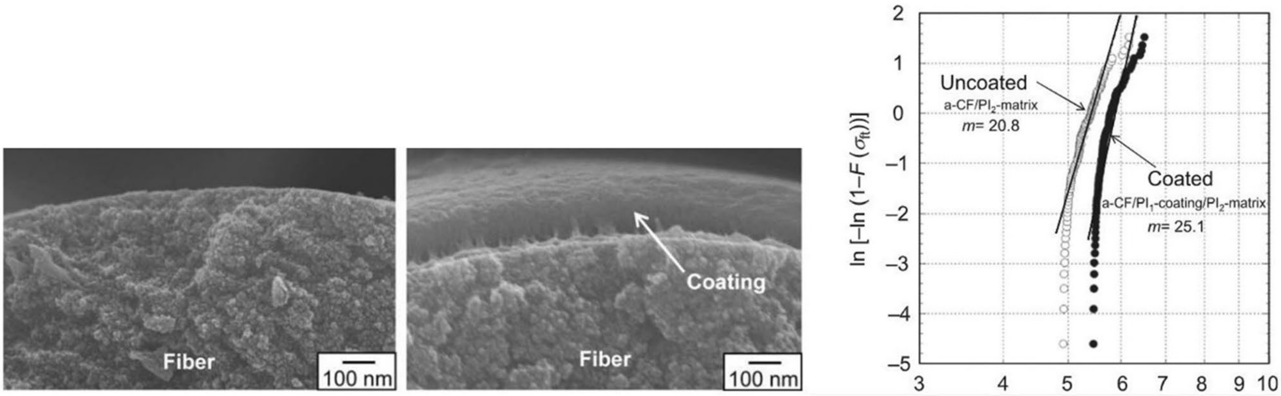


Fig. 12 SEM images and Weibull modulus graphics of the PI coated and non-coated T1000GB carbon fiber [180]

poly(N,N′-bis(phenoxyphenyl)-pyromellitimide) based on PMDA and ODA onto p-aramid yarns with high temperature (350 °C) imidization process to increase tensile strength and thermal resistance [190]. Recently, Hicyilmaz et al. converted conventional fabrics to high performance textile materials by PI coating of polyester and cotton fabrics with low temperature imidization process (at 200 °C) (Fig. 13) [32]. Also flame retardant property of PI coating can be applied onto carbon-blended aluminized (E-glass-based) and non-aluminized (basofil/nomex/carbon-based) firefighting suit fabrics [191]. Furthermore, in wearable energy applications, PI coatings can be applied to provide a smooth surface in multiple layers in cotton, polyester and glass fabrics. By PI coating, surface roughness of the fabrics was decreased and the service life, performance and stability of the dye sensitized solar cells on textiles for wearable energy harvesting applications were increased [192].

5 Commercialization of polyimide coatings and future studies

Optical fibers were used in a wide range of area from medical instruments to industrial laser systems. These materials are very crucial and expensive parts, so they must be protected against environmental conditions. Fiberguide™ produced PI coated optical fibers and fused silica capillary tubes that are used in medical laser, chromatography, bio-analytical sensing, spectroscopy or industrial laser system applications needed high-temperature sterilization or curing process. PI coating provides thermal and dimensional stability to the optical fibers [193]. Fibercore™ produce high and low temperature resistance, flexible and light sensitive PI coated optical fibers. These products are used in geo-sensors, bio-medical sensors, high temperature sensors, or chemical resistance sensors [194]. Thorlabs produces high temperature resistant (up to 350 °C), chemical resistant, autoclavable and vacuum compatible PI coated single-mode and multimode-optical fibers, used in oil and gas sensing, aerospace, military, data communication, and medical applications [195]. iXBlue Photonics is another company that produces PI coated optical fibers with high temperature and radiation resistance [65]. Molex provides PI coated optical fiber and fused silica capillary tubing for medical, scientific and industrial applications [196, 197]. Zeus Inc. provides PI coated tubing and wires [198]. Hilgenberg-GMBH produce PI coated needles that are resistant to bending and cracks [199]. Aculon firm makes nanoscale PI coatings on the metal part, LCD, plasma projection scenes or industrial pipes etc. to obtain hydrophobic and oleophobic surfaces [200]. High dielectric strength PI coating material was developed for insulation of magnets, and different substrates by Composite Technology Development Inc [201]. Also different varnishes most of them based on the PAA precursor solution of PI are in the market for heat resistant coatings [136, 202–207]. On the other hand, coatable PI films or tapes are in the market and commonly used for wide range of applications [8, 208–212].

Morover, PI can be coated on cooking articles to provide resistance to detergents, flame resistance and also, adhesion to an anodized support, thermal conductivity and non-sticking properties [213, 214], and also, glass containers used in several areas such as pharmaceutical packages coated with PI to low-friction property [215].

With the development of technology, the interest and need for high performance polymers has increased. PIs have a wide range of applications from electronics to textiles, and the disadvantages of PIs are reduced by developing new synthesis and production methods. For example; new types of PIs, multi-functional [36, 44, 64, 101,

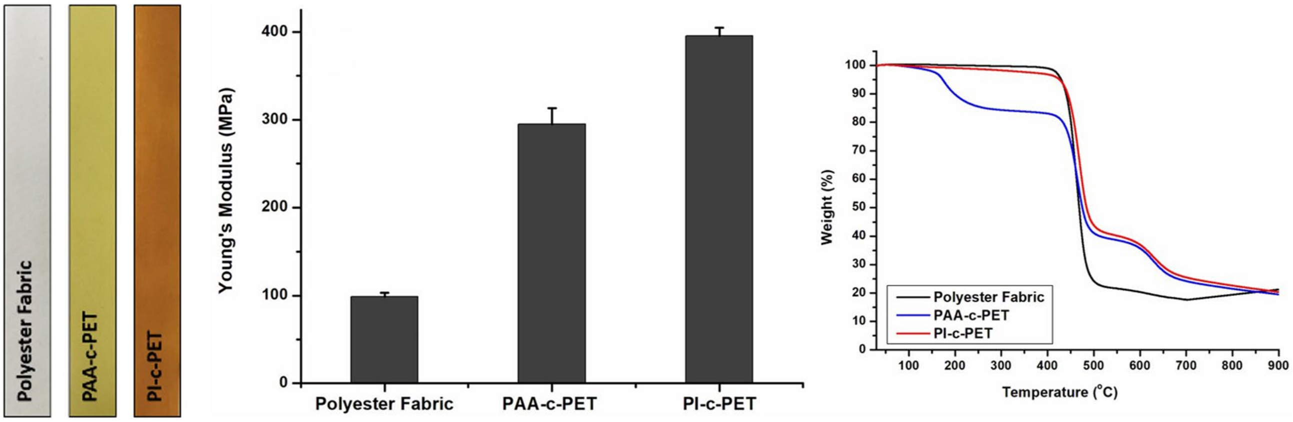


Fig. 13 Images (left), young modulus (middle) and thermal gravimetric analysis (right) graphics of non-coated, PAA and PI coated PET fabrics [32]

216–218], soluble [175, 219, 220] and colorless [221–226] were produced. Furthermore, the properties of PI polymers are further enhanced by the addition of functional micro and nanoparticles such as metal oxides [140, 227–229] and graphene derivatives [230–233]. In recent years, studies have been focused on the synthesis of special PIs for the desired properties [64, 230], as well as the development of low-cost polymer production and coating methods [234]. These developments will expand the application area of the PI coated materials.

6 Conclusion

In this review, the most common coating applications of PIs are summarized, the coating methods and the effects of PIs on coated materials are explained in depth. PI is an important polymer for technical coating applications due to its superior thermal resistance, resistance to external factors and mechanical properties in a wide range of properties. PIs can be applied to various substrates such as various fibers (optical fibers, carbon fibers etc.), metal sheets / wires and textile materials to increase their temperature resistance, corrosion-wear resistance and mechanical strength. It can be used in microelectronic devices and batteries, gas separation systems, medical devices in order to provide insulation against environmental conditions and protection against working conditions, and also in sensor systems for determination of humidity, temperature and salinity. In this context, researchers are working with micro / nanoparticle additives or various synthesis techniques to develop new PI coatings. Especially new coating methods pave the way for the development of high-tech products that require high temperatures in applications such as space. In addition, PI aerogels, foams, membranes and nanocomposites with multifunctional properties have come to the fore in applications in recent years. As a result, future work on PI coatings will focus more on new multifunctional new coating applications and advanced materials including the synthesis of new additives and new types of polyimides.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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