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A Review of Plasma-Assisted Treatments of Textiles for Eco-Friendlier Water-Less Processing

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Abstract

The textile and apparel industry represents a multi-billion market with a wide range of innovations. The comfort characteristics of the textiles goods are of prime importance as they are in close contact with human skin to cover the body and protect it from extreme surroundings. In this article review, the current status and the future prospects of utilization of plasma irradiation in the surface modifications of various textile substrates were outlined. The different types of plasma irradiation used in surface modifications in general, and in textile substrate specifically, were compared. Plasma technology applied to textiles is a dry, environmentally and worker-friendly approach for altering the surface properties of various materials without changing their bulk properties. Because most of the textile materials are heat-sensitive polymers atmospheric non-thermal plasma is the most suitable for textile treatment. In this review article we throw the light on the different types of plasma, their surface interaction and applications on natural and synthetic fibers to improve their surface properties. Special emphasis was directed towards surface modifications of polypropylene fibers using plasma technology.

Keywords: Plasma, polypropylene, polyester, corona discharge, surface modification.

1. Introduction

Various modifications are usually conducted on textile fibres to enhance their appearance, performance and comfort attributes [1]. These modifications adopted chemical [2, 3], physical [4, 5], biological [6, 7], mechanical [8], and combination thereof [9, 10]. Most of the methods adopted commercially in wet processing of textile fabrics consumes huge amounts of water. Among others, these high water-consuming textile wet processes include scouring [11], bleaching [12], and dyeing [13]. Furthermore, great amounts of chemicals are usually utilized in textile dyeing and finishing which brings about pollutants within the discharged effluent [14, 15]. Plasma irradiation would be an appropriate candidate for eco-friendly waterless surface modification of textile substrates.

Plasma is a partially ionized gas and sometimes referred to as the fourth state of matter. Plasmas can be classified into hot (i.e. thermal) plasma and cold (i.e. non-thermal) plasma depending on the temperature of the plasma zone. Only low-temperature plasmas (LTPs) are suitable for surface modification of heat-sensitive polymeric and textile materials [16]. An LTP can be generated by applying an electrical field over two electrodes with a gas in between or by inducing radiofrequency (RF) resonant current in a coil. This can be done in a closed chamber at reduced pressure or at atmospheric pressure. LTPs contain many reactive species including fast-moving electrons, ions, free radicals, and photons in the short-wave ultraviolet range (*c.f.* Figure 1). All of these species can initiate physical and chemical reactions on the surface of a substrate [17]. Such modifications are confined to a few nanometers in depth, implying that the plasma only impacts the substrate's thin surface layer. Thus, LTP treatments can impart many desired functionalities to the surface of textile fibers without altering their bulk properties [18].

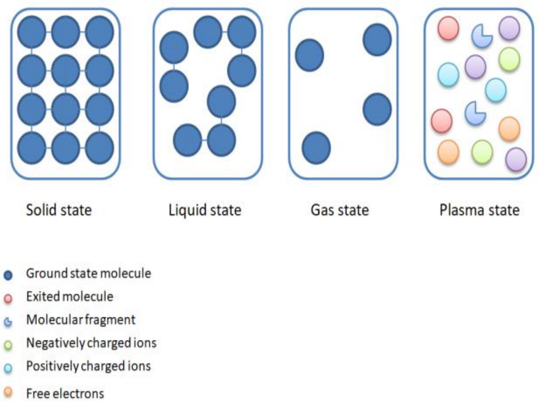

Figure 1: The states of matter

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Primarily, a plasma treatment provides diverse possibilities to treat a polymer surface, enabled by the adjustment of parameters like gas flows, power, pressure and treatment time. Depending on the gas composition and plasma conditions, it is found that, ions, electrons, fast neutrals, radicals and vacuum ultraviolet radiation (VUV) contribute to the polymer treatment, resulting in activation, etching and/or cross-linking [19, 20].

The main cause of polymer surface degradation is the fast interactions with radicals or ions. Here, intensity and duration of the plasma treatment are important. On the other hand, a short plasma treatment causes only outer chain scissions, which may lead to improved surface properties, a more intense treatment also yields inner chain scissions, supported also by VUV radiation [21]. Plasma treatment of polymer surfaces results in not only a modification during the plasma exposure, but also the formation of active niches on the surfaces that are susceptible to post-reactions; this is known as ageing. [22].

The most common applications of plasma for modification of solid surfaces are *a) surface cleaning*, where plasma treatments may be used to clean textile surfaces by removing organic contaminants. For example, they are used for desizing of poly(vinyl alcohol) [23], oxidation of impurities present on cotton fibers [24], eliminating lipids from wool surface, or removing spinning oil from polyester fibers [25]. *b) modification of polymer surface energy*, plasma treatments induce surface oxidation of natural fibers , allowing fibers such as wool or cotton to be dyed more efficiently[24].

Plasma treatments have been also used to improve wettability [26-28], printability [29, 30], dyeability [31, 32], and adhesion promotion of both natural and man-made fibers. Kim and Kang showed that the adhesion of silicone coating to wool fabrics increased following an oxygen (O_2) plasma treatment [33]. Qui *et al.* succeeded in increasing the adhesion between polyester (PE) fibers and epoxy resin using atmospheric plasma treatment of PE fibers with a mixture of oxygen (O_2) and helium gases [34-36]. Plasma also was used for degradation of hardly removed textile dyes in wastewater using dielectric barrier discharge (DBD) plasma method [37].

2. Different Types of Plasma

Because there are so many different kinds of plasma, it's difficult to make a universal classification. However, the first simple and objective way to classify different kinds of plasma is to divide it into two categories: thermal and non-thermal [38]. Thermal plasmas can also be artificially generated using several methods, such as DC or AC electrical discharges (free burning, pulsed and transferred arcs, plasma torches), RF (Resonance Frequency), laser and microwave discharges at near-atmospheric pressure [39].

In thermal plasmas, the temperatures are extremely high (some thousands degrees Celsius) and are characterized by the condition of thermal equilibrium between all the different species contained in the gas. Thermal plasma can be observed in the stars, lightings, northern lights and other celestial bodies. No textile material can withstand the destructive nature of this type of plasma, thus it is not a topic for discussion.

Non-thermal plasmas are those in which the thermodynamic equilibrium is not reached even on a local scale between the electrons and the higher mass particles (neutral atoms or molecules, ions and neutral molecules fragments). In this type of plasma, the temperature of the electrons is much higher than the temperature of other particles. The electrons can reach temperatures of 104–105 °K (1–10 eV), while gas temperature remains near to room temperature [40].

Non-thermal plasmas, also called cold plasmas, are particularly suited for textile surface modification and processing because most textile materials are heat sensitive polymers [41]. It has been observed that such discharges have the major advantage of causing considerable surface chemical and morphological alterations, thus enhancing hydrophilicity and making fibres more susceptible to different chemical species without affecting the materials' bulk properties [42, 43].

3. Classifications of Non-Thermal Plasma

Cold plasmas may be divided into atmospheric pressure plasmas and vacuum or low-pressure plasmas. The advantages and disadvantages of these two plasma kinds are still being debated. The choice of the process to be applied depends on the processing speed, sample size and extent of the intended modification [44]. Several research groups have concentrated their efforts on modifying polymer surfaces with plasma treatments using various gases. Most of the work done on that field has been accomplished with low pressure plasma treatments. Vacuum plasma is often used to achieve various effects by etching, polymerization or formation of free radicals on the surface of the textile substrate [45]. On the other hand, low-pressure plasma (LPP) technology necessitates expensive vacuum systems, making it difficult to scale up and achieve continuous processing. These factors have seriously limited the commercial viability of this technique in the textile industry [46].

Recent research on plasma generated at atmospheric pressure has proven excellent results in surface modification of textiles and a variety of other materials in terms of stability, uniformity, and workability [41, 47, 48].

Atmospheric plasmas are a cost-effective and alternative to low-pressure plasma and wet chemical treatments, as they do not require expensive vacuum equipment and allow for continuous and homogeneous surface processing [49].

There are four main types of atmospheric plasmas applied to textiles:

(i) Corona discharge: Corona is the oldest plasma technology applied on the modifications of polymer surfaces. At atmospheric pressure, a corona discharge is induced by applying a low frequency and a high voltage (10–15 kV) between two electrodes of various shapes and sizes. As the distance between the electrodes decreases, the discharge energy density decreases dramatically, requiring extremely close interelectrode spacing. (~1 mm), which is incompatible with thick materials and rapid, consistent treatments. Corona treatment may enhance the surface area and surface roughness of fibres, but it is an uneven treatment for textiles since its ionization is non-uniform, impacting primarily loose fibres and not penetrating deeply into fabrics [50].

(ii) The dielectric barrier discharge technology (DBD): Is one of the most successful non-thermal atmospheric plasma sources, and its adaptability to very large systems has piqued interest for industrial uses [48]. In DBD plasma a dielectric layer covers at least one of the electrodes, accumulating the transmitted charge on its surface. The dielectric layer has two functions: It reduces the amount of charge that may be transferred by a single micro-discharge and evenly distributes the charge throughout the electrode's surface. However, DBD is not completely uniform and has short duration. This can interrupts the sequence of chemical reactions required to produce important species [51].

(iii) Atmospheric pressure glow discharge (APGD): Is generated by a lower voltage and a higher frequency when compared with DBD plasma and it is characterized by uniformity, a relatively long duration, and low-to-moderate areal power densities avoiding surface heating or damaging. A radio-frequency source is connected between two parallel electrodes, separated by few millimetres. The electrodes must be conductive to maintain a DC glow discharge. In the simplest case, a discharge is created by applying a potential between electrodes inserted into a cell containing a gas, commonly helium or argon, at atmospheric pressure, ranging from a few kV to 100V. [52].

(iv) Atmospheric pressure plasma jet (APPJ): It's a considerably milder than a plasma torch, but it's still a powerful method at room temperature. Plasma jet has an advantage over DBD in that it can produce homogenous reactive gases and can be applied to any shaped object's surface. However, only one side of the treated material towards the plasma jet can be treated with APPJ. [53].

The effect of plasma treatment on textile substrates

Despite the high potential advantages, environmentally friendly and application possibilities of plasma technology, but its use in textile industry is still limited due to three main problems: (i) Surface cleanliness, since plasma treatment only influences the top layer, contaminations or different surface conditions of the textile could have significant negative effects. (ii) Three dimensional structures of textiles, where plasma species could not penetrate deep enough into the fabric structure to assure adequate treatment as wet treatments may. The pressure at which the plasma treatment is performed is a critical variable in this respect. (iii) Large surface area, where textile materials as composed of individual fibres, are characterized by a large surface area, usually one order of magnitude larger than flat films [54].

In spite of these limitations, plasma technology has been employed for several specialized applications in the textile industry. It is also used in new and improved methods for wider application in recent years due to continual technological developments and scientific research efforts. In the textile industry vacuum plasma technology has advanced significantly faster than atmospheric-pressure plasma technology because: (i) it is more simple tool producing large volumes of plasma at reduced pressure than at one atmosphere; (ii) it is easier to control the concentration, composition and process chemistry of the atmospheric gas in a closed system under vacuum; and (iii) atmospheric plasmas are characterized by a higher collision ability and a lower fractional ionization than vacuum discharges [55].

4. Action of plasma on material surface

When a material is exposed to plasma beam, it is attacked by a range of plasma particles (electrons, ions, radicals, and neutrals) as well as UV photons of different energy that hit the surface. Some of these active species have enough energy to break down chemical bonds and start reactions on the fibre surface. Due to the complexity of the gas phase and the polymer composition, it is difficult to isolate and study the unique roles of each plasma component. [56].

The alterations that result are depending on the type of the textile substrate as well as the working gas. Oxygen, air, argon, helium, carbon dioxide, nitrogen, hydrogen, tetrafluoromethane, water vapour, methane, or ammonia are some of the gases or mixtures of gases used for plasma treatment of textiles [57, 58]. Each gas produces a varied plasma composition, which results in various surface properties. Helium, argon, nitrogen, and oxygen plasmas, for example, can activate surfaces via ablation or etching. The impact energy of the ions, which is determined by the pressure and input power, affects the amount of etching and roughening of the surface.

There are four bases that essentially depend on the plasma treatment conditions: surface cleaning, etching, surface activation, and polymerization.

5.1. Surface cleaning

Surface cleaning is the process of removing impurities and pollutants from the substrate surface, such as oils, greases, and oxides. Contaminants are volatized and eliminated during plasma cleaning, but the substrate's bulk properties are unaltered. Because of its high ablation effectiveness, chemical inertness with the surface material, and low cost, argon is the most often employed noble gas in plasma treatment [59].

5.2. Surface etching

Plasma etching is the process of physically removing surface material from a treated substrate and forming volatile compounds through chemical reactions at the surface. Lower molecular weight fragments will be present on the etched surface. Inert gases (argon, helium, etc.), nitrogen or oxygen plasmas are commonly used in surface etching. The etching rate is affected by plasma composition, kind of substrate, and working conditions (power, gas flow, substrate position).

5.3. Surface activation

Surface activation is the process of introducing new functional groups to the treated substrate in order to change its surface energy and give it new features. Plasma activation takes place in non-polymerizing gases. The reactive plasma species that hits the surface breaks covalent bonds and produces free radicals on the treated substance. These surface radicals react with the active plasma species to create active chemical functional groups on the substrate surface, such as hydroxyl, carbonyl, carboxyl, and amino groups (*c.f.* figure 2). The chemical activity and properties of the surface are altered as a result of this activation. Oxygen plasma, for example, causes the grafting of polar and hydrophilic functionalities, increasing the material's surface energy. Surface activation is primarily used to elevate the surface energy of textile materials in order to improve their wettability, printability, or adhesive properties. [36].

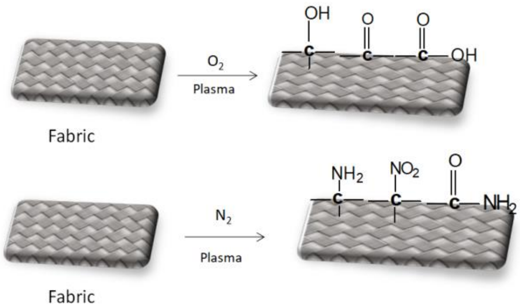


Figure 2: Creation of functional groups in plasma-irradiated textile fabric

5.4. Polymerization

Plasma polymerization involves the polymerization of an organic monomer such as tetrafluoroethylene (C_2F_4), or hexafluoropropylene (C_3F_6) in plasma to generate a thin polymer coating on the substrate surface. The procedure begins with plasma irradiation of the surface, which prepares it for coating via activation, resulting in reactive bonding sites. During polymerization process, the plasma deposits molecular fragments and grafts them to the surface [60, 61].

5. Applications of plasma in textile industry

Plasma treatments find their application in the textile field for a variety of purposes including modification of surface energy, modification of surface topography, surface cleaning, improvement of adhesion and hydrophilicity (*c.f.* figure 3).

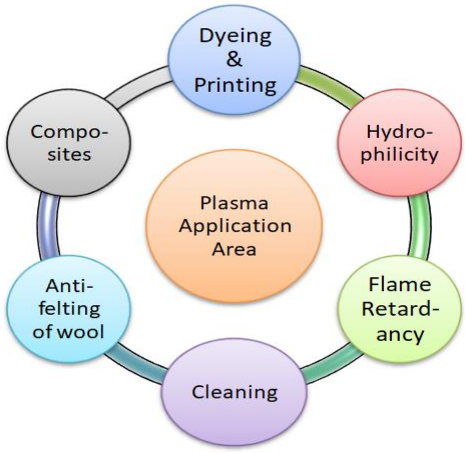


Figure 3: The different applications of plasma on textiles

5.1. Improving hydrophilic properties

Many attempts have been reported to enhance fibre surface hydrophilicity [62-64]. Plasma treatment has been shown to increase the surface energy and improve the hydrophilic characteristics of textile substrates. The changes in surface energy are primarily due to the formation of polar functional groups on the fabric surfaces during plasma or through post plasma reactions. The consequences of enhanced wetting properties are multiple and of great interest to textile manufacturing. However, given the heterogeneous structure of textile materials, the evaluation of the wettability of plasma treated surfaces is usually done by indirect methods such as wetting time and wicking [65]. Figure 4 compares between the behavior of a hydrophobic and plasma-treated hydrophilic surfaces towards water vapour, while the former can't form hydrogen bonds with water vapour molecules, the latter can via any polar groups such as hydroxyl, carboxyl, and amino groups.

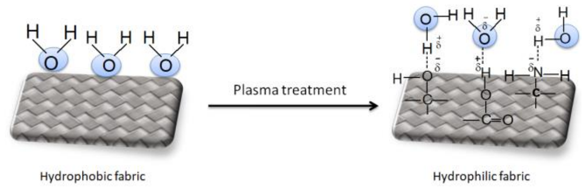


Figure 4: Hydrophilicity of plasma-treated fabrics

6.2. Treatment of natural fibres with plasma

Natural fibres, including cotton, wool, and silk, exhibit many properties that meet the customer demand. Nevertheless, each of the said fibres have some drawbacks which were addressed in previous investigations [66] [67]. Karahan and Ozdogan studied the effect of raw cotton fabric treatment by DBD plasma using air and argon gases. They found that the hydrophilicity and the wickability of plasma-treated samples increased considerably where argon plasma was more effective than air plasma treatment. This finding was attributed to the significant etching effect of noble gas. The authors concluded that plasma treatment can be used as an effective technique for modifying the surface properties of cotton fabric without altering the interior part of the fiber [28].

In another study Cai and Qui found that both air/helium and oxygen/helium atmospheric plasma treatments decreased the water contact angle of wool fibers from 132.4° to almost 123 C° and hence enhanced the initial dyeing rate, in case of acid dyeing [68]. However, the oxygen/helium-treated samples absorbed water more quickly than the air/helium-treated ones. This result was probably due to formation of larger number of hydroxyl or carbonyl groups on the oxygen/helium plasma-treated fiber surface. Similar results using wool fabrics treated with helium and oxygen/helium APPJ were reported by many authors [69-71].

A number of studies have shown that plasma treatment can improve the significant shrink-resistant and anti-felting effects to the wool fabrics [72]. The improvement is attributed to the reduction in the directional frictional coefficient (DFE) of the fabric, resulting in the decrease in the felting tendency of the wool. Wool fabric treated with LTP using non-polymerizing reactive gases, such as O_2, N_2 and Ar. The results show that not only the topography of the surface is modified but also the chemical composition of the surface. It is also shown that the wettability and dyeability of the wool could be increased under the proper conditions. The decrease in the water absorption time and increase in the dyeability of wool are attributed to the modification of its scaly structure due to plasma etching on a wool surface and the introduction of more polar groups such as carboxyl groups [73]. Höcker used vacuum fluorocarbon plasma treatment to render cotton fabrics waterproof and breathable. When hexafluoroethane plasma is utilized, the surface composition of the fibers affirms the presence of fluorine and the material becomes highly hydrophobic leading to what is called "Lotus effect" [24].

6.3. Treatment of Synthetic fibres by plasma

Surface modification of synthetic fibers for various applications is considered as the one of the best methods to obtain modern textile finishing processes [74, 75].

Synthetic fibers, viz., polyethylene terephthalate (PET), polyamide (PA), polyacrylonitrile (PAN) and polypropylene (PP) are the most widely used polymers in textile industry. These fibers exceed the production of natural fibers with a market share of 54.4% by virtue of their versatile performance attributes. Besides their beneficial properties, they show various disadvantages such as hydrophobicity, less wearing comfort, low dyeability, build-up of electrostatic charge, the tendency to pilling, difficulties in finishing and insufficient washability associated with their hydrophobic nature.

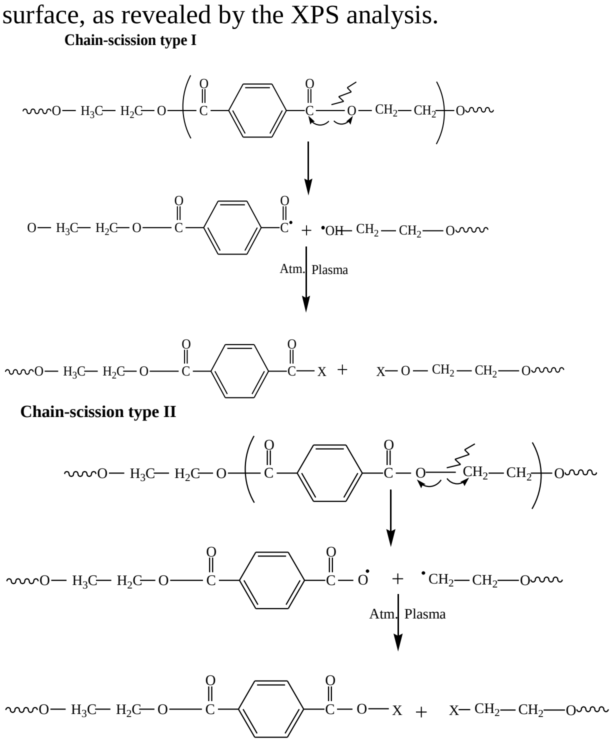
It was found that synthetic fiber surfaces may be oxidized using atmospheric plasma treatment [76, 77]. Plasma treatments of synthetic polymers, decreased the water contact angle on these surfaces after treatment: for a non-woven PP (polypropylene) contact angle decreased from 110° to 42°, for a PE (polyethylene) film, it decreased from 105° to 50° and for a PET film decreased from 90°to 15° [76, 77].

Hydrophobic surfaces can also be created using fluorocarbon plasma treatments. These treatments are not carried out at atmospheric pressure but with vacuum plasmas [26]. Khairallah *et al*. give details on fluorocarbon plasma treatments of PE film [24] and non-woven PET needle felts [26]. The amount of fluorine at polymer surfaces was found to increase with the treatment time.

It is worth mentioned that, the fiber nature and structure of fabrics have an effect on the results obtained from atmospheric-pressure plasma treatment. For example, it was found that, for atmospheric-pressure plasma treatments on polypropylene (PP) and polyamide (PA) fabrics, PP fabric achieved better hydrophilicity than the PA fabric [78]. Morent *et al.* showed that medium-pressure DBD plasma treatments of nonwoven PP and PET fabrics using different gases namely air, helium, and argon resulted in a higher wettability for the PET nonwovens compared to the PP nonwovens [79].

An aging study revealed that the loss in wettability for the PET nonwovens was much higher than for the PP nonwovens during storage. Thus, it can be concluded that the degree of plasma hydrophilization depends on the nature of fibers [16].

Leroux *et al.* [80] investigated the effects of atmospheric-pressure air plasma treatments on different shapes of PET such as film, nonwoven and woven fabrics. It was observed that the water contact angle decreased from an initial value around 80° to 40–50° depending on the material structure. The enhanced wettability was attributed to the introduction of hydroxyl and carboxyl groups on the PET fiber surface, as revealed by the XPS analysis.



Where X is -OH or -COOH

Scheme 1 proposed reaction mechanism **of** Chain-scission occurring during air-plasma treatment of polyester

Hossain *et al.* showed that low-pressure plasma treatments using oxygen-containing gaseous mixtures (Ar/O_2, He/O_2) significantly improved the wettability of PET fabrics with varying construction and yarn type. In addition, they found that the extent of improvement in hydrophilicity was much greater for looser structured fabrics, such as knitted fabrics, than tightly woven fabrics. This result was explained by the fact that the reactive gas particles easily moved into inter-yarn and inter-fiber spaces in the looser structured fabrics, causing deeper penetration of plasma surface modification into the fabrics, resulting in improved wettability or capillarity. Thus the dependence of plasma treatments on the fabric structure can be obviously concluded [81].

Yip *et al.* applied a 193 nm argon fluoride excimer laser on polyamide 6 fabrics. Micrometer-sized ripple like structures were developed on the surface of irradiated fabric and chemical analysis indicates that carbonization has occurred. It is believed that the laser treatment breaks the long chain molecules of nylon, thus increasing the number of amine end-groups [82].

The following part of review will focus on the different surface modifications of polypropylene using different plasma techniques.

7. Polypropylene

7.1. Chemistry of preparation of polypropylene

Coordination polymerization is a chain polymerization in which both the monomer and the active centre is coordinated to polymerization catalyst prior to incorporation of the monomer in the polymer chain. The polymerization exhibits various degrees of sterochemical on the structure of the polymer depending on the nature of the catalyst and reaction conditions. Ethylene, α-olefins and conjugated dienes are the most important polymers that are polymerized [83]. Ziegler-Natta catalysts are used for the polymerization of olefins where the catalyst is used to reduce the activation energy for the polymerization process thereby speeding up the reaction and allowing it to proceed even under mild conditions. This catalyst was utilized by Giulio Natta to polymerize propylene into crystalline PP polypropylene [84]. As the active sites of the catalysts are not identical so, the polymerization of propylene yields PP backbone could be crystalline (isotactic), amorphous (atactic) or syndiotactic (*c.f.* figure 5) [83]. Side chains could be ethene, propene, or ethene/propene macromers. All these branched polymers show different properties concerning their crystallization behaviors, molar masses, stiffness, or processibility.

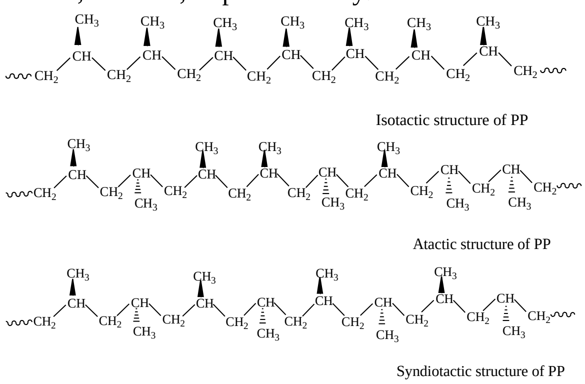


Figure 5: Different microstructures of polypropylene

7.2. Surface modification of polypropylene by plasmas

Polypropylene (PP) is a polymer with good mechanical properties which has been used in a wide range of applications. However, due to its inertness and low surface energy, PP has to be surface-treated for applications in coatings, bonding, printing and metallization [85]. The frequently used surface treatments for PP include plasma, corona and flame treatments. Plasma treatment of polymer surfaces has been studied extensively for many years. In spite of these disadvantages, plasma treatment of polymers is an attractive process to produce the required surface modification. By using different types of gas, various chemical functionalities can be introduced on the surface. In general, more uniform surfaces are produced by plasmas.

In addition to surface modification of polypropylene films prior to adhesive bonding, printing with inks, lamination to other films and other coating applications by corona discharge treatment (CDT), Lesley-Ann *et al.* treated polypropylene film with corona discharge to investigate the physico-chemistry of the surface using some surface analytical techniques viz., contact angle analysis; x-ray photoelectron spectroscopy (XPS); atomic force microscopy (AFM).

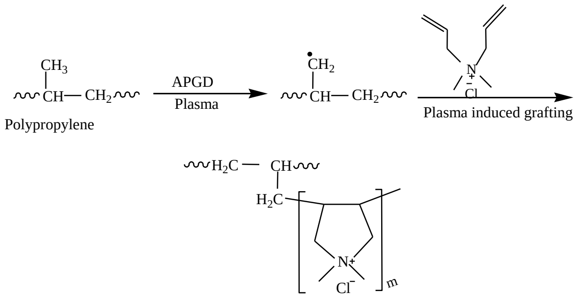
The surface energy was found, to increase with increasing energy of the corona. The functional groups incorporated onto the surface have been identified as hydroxyl [–OH], peroxy [–O–O], carbonyl [C=O], ester [–O–C=O], and carboxylic [HO–C=O] [86].

It has been reported that, low-pressure plasma treatments of O_2 and Ar were employed to introduce polar functional groups onto the biaxial-oriented polypropylene (BOPP) surfaces to enhance its wettability. In order to increase in the surface energy of BOPP films due to O_2 and Ar plasma treatments was observed. The surfaces became highly hydrophilic when exposed for 20 s or longer to the plasma discharge. The wettability of polymer surface can be improved when oxygen functionalities are generated, which can be achieved directly in O-containing plasmas or via post plasma reactions. AFM and SEM images revealed distinct changes in the topography of BOPP due to O_2 and Ar plasma treatments [87].

Diallyldimethylammonium chloride (DADMAC) was grafted onto PP nonwoven fabric by pre-activation and post-treatment by APGD plasma (99% He/1% O_2). Polypropylene samples were subjected to plasma pre-activation followed by padding with DADMAC and pentaerythritol tetraacrylate (as a cross-linker to increase the durability of the coating), then drying, plasma-induced graft polymerization, and rinsing (*c.f.* scheme 2). The treated samples showed good antimicrobial activity against Staphylococcus aureus (S. aureus) and Klebsiella pneumoniae (K. pneumoniae) bacteria [88].

Polypropylene (PP) fabrics were activated by an atmospheric pressure, dielectric barrier discharge to optimize the effects of some discharge parameters on the dyeability of PP fabrics.

Air and argon plasmas were used to modify the surfaces of the PP fabrics, to increase their dyeability when before dyeing with leuco and pigment forms of vat dyestuffs. The increase in dyeability can be attributed to increased microroughness, increased surface area, and the addition of functional groups, such as carbonyl, carboxyl and hydroxyl, to the fabric surface (*c.f.* scheme 3). The introduction of hydrophilic groups induced by both reactive and chemically inert plasmas, may increase the water swelling capability and the affinity of PP fibers to dyestuff containing polar groups [89, 90].



Scheme 2. Schematic presentation of plasma-induced graft polymerization: proposed reaction mechanism of attachment of DADMAC on PP nonwoven by plasma activation

Hydrophilicity can be achieved by treating PP film in plasma for a shorter duration and maximum bonding strength can be achieved by treating PP film for a longer time. Biaxially oriented polypropylene films (BOPP) film gives a high value of surface energy than unoriented polypropylene (UPP) mainly because of more surface roughening, but the bondability achieved after treatment was less than that of UPP. The induced crosslinking in BOPP was found to be more than UPP film, but on aging, the induced crosslinking on the UPP surface was found to be more stable [91].

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Scheme 3. Proposed reaction mechanism of surface crosslinking for PP when treated in air and nitrogen plasma and surface hydrophilic modification for PP when treated in oxygen and nitrogen plasma.

Future outlook

The use of plasma irradiation as a tool for textile substrate on an industrial scale requires new innovations to match with the conventional machinery and technology. Plasma irradiation would be coupled with some eco-friendly modifications utilizing benign reagents. The role of plasma irradiation would be surface activation of the textile fabric through formation of hydrophilic functional groups. These groups would represent the active sites for further modifications using new renewable biopolymers. These biopolymers are cheap available materials which sometimes represent polluting wastes.

Utilization of plasma technology in textile industry would save huge amounts of water, energy, and chemicals which are used in conventional wet processing of textile fabrics.

Conclusion

Plasma technology is highly recommended in textile industry as a water and energy-saving tool to impart special modification to fabrics taking into consideration environmental concerns.

Low-temperature plasma technique has a versatile, clean, and eco-friendly finishing approach for introducing desired functional properties to textile to meet specific requirements. For example, the discharge of harmful chemicals can be eliminated, improving of surface hydrophilicity or enhancement of dyeing using plasma technique.

The choice of the best plasma process to be applied to textile whether atmospheric or a low-pressure technology depends on the processing type, speed, sample size and extent of the intended modification. However, atmospheric plasma technologies (APT) have been effectively applied as a convenient alternative and cost-competitive method.

The main conclusions reached in this review about recent APT improvements are:

- The surface properties can be improved selectively in relatively short processing times without compromising the bulk properties of the treated material,
- Plasma treatment can be used to create new surface properties that cannot be obtained by traditional wet chemical finishing. Thus, plasma technology can make important contribution to sustainable growth, innovation, and new products,
- Corona plasma discharge has been obscured due to its lack of uniformity,
- APT considerably improved the efficient dyeing of polypropylene, polyamide and wool fabrics.

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