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REVIEW

A review of low-temperature plasma treatment of textile materials

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Abstract In recent years, plasma treatment technology has attracted more attention in the textile industry, as it seems to be a promising economically and ecologically sound alternative to conventional wet-chemical processing techniques. Plasma surface treatment is a relatively simple process that is clean, solvent-free, time saving, and environmentally friendly. Moreover, plasma treatments offer the possibility to obtain typical textile finishes without changing the key textile properties. The efficiency of plasma treatment depends on several factors including the nature of the substrate and the treatment operating conditions. However, the application of plasma technology to different kinds of textile materials has not been fully exploited. This paper presents a review of the current literature on the surface modification of textiles by low-temperature plasma (LTP) technology. Its main objectives are to (i) investigate the influence of LTP treatment on the surface properties of natural and man made textile materials, (ii) outline the contribution of LTP treatment towards sustainable development, and (iii) examine the hurdles that LTP has to overcome in the textile industry.

Introduction

Surface treatment of polymeric textile materials is usually necessary to alter their surface characteristics and to improve their adhesion properties. Traditional liquid chemical processes used by the textile industry consume substantial volumes of water and chemicals, which are frequently toxic, and produce huge quantities of effluents requiring expensive purification treatments. Due to their detrimental effect on the environment, the textile industry is strongly motivated to seek alternative dry finishing processes that could offer lower cost, environmentally friendly manufacturing and routes to new products with improved quality and performance. Plasma-based processing may provide an attractive approach for the surface treatment needs of the textile industry as it is regarded as a dry, green process since it does not require the use of water and chemicals. Moreover, the treatment time (just a few seconds in many cases) reduces energy consumption. Since the early 1980s, many laboratories around the world have looked into the effects that low-pressure plasma treatments on different textile materials showing very promising results [1–3].

A plasma is a partially ionized gas and is sometimes referred to as the fourth state of matter. Plasmas can be classified into hot/thermal plasma and cold/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. 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 carried out in a closed vessel under reduced-pressure or at atmospheric-pressure. LTPs contain many reactive species including fast-moving electrons, ions, free radicals, metastables, and photons in the short-wave ultraviolet range. All of these species can initiate physical and chemical reactions on the surface of a substrate [4]. Such changes are confined to a depth of a few nanometers, i.e., the plasma only affects the outermost thin layer of the substrate. Thus, LTP treatments can impart many desired functionalities to the surface of textile fibers without altering their bulk properties [5]. The

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changes induced are governed by several factors such as the type of gas used, pressure, frequency, power, treatment time, as well as the nature of the substrate. Plasma treatments are therefore very versatile and multifunctional. In the past, the most common applications were surface cleaning and surface coating. More recently, plasma treatments have been used to improve wettability [6–12], printability [13–15], dyeability [16–18], and adhesion promotion of both natural and man-made fibers [19–21].

The apparent potential of LTP technology for textile pretreatment and finishing processes has led to the development of machinery allowing treatments to be carried out at low-pressure and under atmospheric conditions. Low-pressure plasma sources operate under vacuum, usually between 0.01 and 10 mbar, and are characterized by their high concentration of reactive species, superior chemical selectivity, and good uniformity over a large surface area. The advantage of these sources is that they are highly controllable and provide reproducible results. However, in many cases, low-pressure plasma treatments have proved difficult to upscale specially for continuous processing. Being confined to batch processing is a serious limitation in terms of commercial application. Moreover, the sample size is limited to the size of the reactor. Hence, the generation of large-scale reactive plasmas at low-pressure requires the use of large-size vacuum chambers and complex vacuum equipment, which is in turn expensive in both capital and running costs [5]. These costs have to be reflected into the final product price.

In an attempt to overcome the deficiencies of low-pressure plasma employment, atmospheric-pressure plasma systems were developed to fulfill the need of textile industry. As the name suggests, these systems process materials at standard atmospheric-pressure. They offer basic advantages in terms of investment cost and process integration since they did not require any vacuum system and are adaptable with continuous fast-running textile production and existing finishing lines [22]. In coating application, however, running costs might be higher given that atmospheric-pressure plasma requires high flow rate of the filling gas in order to provide a sufficiently defined plasma atmosphere and to obtain a drift of the reactants to the surface, since convection processes have to be overcome [23].

There are four main types of atmospheric-pressure plasma which can be used for application on textiles, namely corona discharge, dielectric barrier discharge (DBD), atmospheric-pressure glow discharge (APGD), and atmospheric-pressure plasma jet (APPJ) [5].

The corona treatment is the longest established and most widely used plasma process. Corona discharges can be generated using several different electrode configurations. The discharge is very weakly ionized and contains inhomogeneous initial electric fields formed around pointed electrode elements. Unfortunately, this filamentary character results in a non-homogenous surface treatment and there is the risk of damaging the substrate. Also, corona systems rely upon very small inter-electrode spacing ($\sim$1 mm) and accurate positioning, which are incompatible with the treatment of "thick" materials and rapid treatments [5].

DBDs are promising for textile processing. It is characterized by the presence of an insulating layer (e.g., ceramic or glass plate) over one or both of the electrodes and usually consists of many small current filaments (micro-discharges). The role of the dielectric is to limit the current thus avoiding the gas spark or breakdown. A major advantage of DBD over corona discharges is its higher electron density leading to improved textile treatment uniformity. However, the micro-discharges are not completely uniform and have short duration and thereby they have potential to cause an uneven treatment of the textile [5].

An APGD is uniform, homogenous, and relatively stable and is usually generated in helium or argon (and some times nitrogen). It is analogous in its mode of generation and some key characteristics to the low-pressure glow discharge plasma, while operating at atmospheric-pressure. The main advantage of APGD over filamentary DBD is that it provides a uniform plasma which is essential for the deposition of homogenous thin film and uniform surface treatment [5].

APPJ represents the latest development in atmospheric-pressure glow discharge for surface modification of polymers and textiles. A key aspect of this technology includes the use of helium and other proprietary gas blends to inhibit arcing. APPJ enables a plasma treatment to be applied to textile fabric in situ mode [5]. It has advantages over DBD because it can generate uniform reactive gases and can be applied to the surface of any shaped object. However, APPJ can only be applied to one side of the treated material directly facing the plasma jet.

To date, however, there is no single ideal and clearly superior atmospheric plasma technology for textile manufacturing. Atmospheric-pressure plasmas are not intrinsically superior to low-pressure plasma. Each technique has different attributes and strengths. Thus, the textile manufacturer needs to select the plasma equipment that delivers the required level of surface functionalization, manufacturability, and commercial performances at the lowest cost and highest margin. Despite the proven capability and flexibility of plasma technology in the laboratory environment, plasma processing on an industrial scale has been slow to make an impact in the textile industry. Some of these factors may include the three-dimensional structure of the textile substrates, the large effective surface area (because of the individual fibers) to be treated, and the aging factor of plasma-treated materials. Therefore, a basic understanding of the effect of plasma processing conditions and their interaction with the textile substrates is still needed in order to effectively utilize the advantages of this novel technology.

In literature, there have been a number of significant reviews on the LTP treatment of polymers [24–26] and textile materials [27–30]. This paper reviews recent studies on the plasma surface modification of textile materials paying particular attention to the influence of textile structure and plasma processing parameters on treatment results. It also outlines the contribution of LTP treatment towards sustainable development and examines the limitations of the plasma technology in the textile industry.

The effect of plasma treatment on textile substrates

LTPs can be used for various treatments such as functionalization and etching of surfaces, plasma polymerization, and grafting films onto many types of substrate such as glass, metal, and ceramics.

Plasma surface interactions

When a material is exposed to plasma, its surface is bombarded by a variety of plasma particles (electrons, ions, radicals, and neutrals) and by UV photons which hit the surface with a distribution of different energies. Some of these active species are energetic enough to dissociate chemical bonds and initiate reactions on the fiber surface. The specific roles of each plasma component are difficult to separate and analyze, due to the complexity of the gas phase and the polymer composition [31]. The depth of the substrate that is influenced by photons can be up to several tens of nanometers; for all other particles, the interaction depth is confined to about 10 nm or less [32]. For porous textiles, however, the active species in plasma can penetrate through the larger pores in materials and can modify other inner surfaces [33] and in some cases, this is crucial [34]. The resulting changes depend on the nature of the textile substrate and on the working gas used. Gases, or mixtures of gases used for plasma treatment of textiles can include oxygen, air, argon, helium, carbon dioxide, nitrogen, hydrogen, tetrafluoromethane, water vapor, methane, or ammonia [35, 36]. Each gas produces a unique plasma composition and results in different surface properties. For example, plasmas generated with helium, argon, nitrogen, and oxygen can activate surface by means of ablation or etching. The amount of etching and roughening of the surface is governed by the impact energy of the ions which in turn is governed by the pressure and input power.

Essentially, four main effects can be obtained depending on the treatment conditions: surface cleaning, etching, surface activation, and polymerization.

Surface cleaning

Surface cleaning involves the removal of impurities and contaminants such as oils, greases, and oxides from the substrate surface. During plasma cleaning, contaminants are volatized and removed, while the bulk properties of the substrate remain unaffected. Argon is by far the most common noble gas used in plasma treatment because of its high ablation efficiency, chemical inertness with the surface material, and relatively low cost [37].

Surface etching

Plasma etching consists in removing surface material from the treated substrate surface by physical etching and chemical reactions at the surface to form volatile products. The resulting etched surface will contain lower molecular weight fragments. Inert gases (argon, helium, etc.), nitrogen or oxygen plasmas, are typically used for the etching of polymers. The etching rate depends on several parameters like plasma composition, substrate nature, and working conditions (power, gas flow, substrate position). For example, Matthews et al. [38] showed that oxygenated-helium plasma treatment achieved a higher etching rate of PET film compared to etching in helium-only plasma. This result was attributed to the chemical reaction of atomic oxygen with the polymeric film surface. Taylor and Wolf [39] studied the oxygen plasma etching behavior of 40 different polymers and found that the strength of the polymer backbone bonds mainly determined the rate of weight loss in most cases. Strong (covalent) backbone bonds, aromatic and polar functional groups, and the presence of organometallic polymers such as poly (dimethyl siloxane) decreased the removal rates. Weak bonds not attached to the polymer backbone had little effect on the etching rate, while weak bonds attached directly to the chain or in the chain such as hydrogen bonds greatly accelerated removal. Sprang et al. [40] and Zeuner et al. [41] found that plasma etching rate of a given polymer increased with discharge power. Upon higher energy input, the density of plasma reactive species as well as their acceleration towards the substrate would increase, resulting in more severe etching of the substrate's surface.

Surface activation

Surface activation consists in the introduction of new functional groups onto the treated surface in order to give it specific properties by varying its surface energy. Plasma activation is performed in gases that do not polymerize. The bombardment of the surface with the reactive plasma species breaks covalent bonds and creates free radicals on the treated material. These surface radicals react with the active plasma species to form various active chemical functional groups such as hydroxyl, carbonyl, carboxyl, and amine groups on the substrate surface. Such activation alters the chemical activity and characteristics of the surface. For example, an oxygen plasma leads to the grafting of polar and hydrophilic functions which increase the material surface energy. On the other hand, a carbon tetrafluoride (CF_4) plasma leads to the surface fluorination and induces anti-adherence properties. Surface activation, however, is mainly used for treating textile fabrics to raise their surface energies in order to improve their characteristics of wettability, printability, or adhesion [20].

Polymerization

In plasma polymerization, a thin polymer coating is formed at the substrate surface through polymerization of an organic monomer such as methane (CH_4), ethane (C_2H_6), tetrafluoroethylene (C_2F_4), or hexafluoropropylene (C_3F_6) in plasma. The process proceeds through plasma bombardment of the surface preparing it for coating by activation to create reactive bonding sites. The plasma then deposits molecular fragments and grafts them to the surface while carrying out polymerization [28, 42]. The deposited thin coatings can possess various properties, depending on the specific gas and process parameters selected. Such coatings exhibit a higher degree of cross-linking and extremely stronger adherence to the substrate in comparison to films derived from conventional polymerization. Due to these properties, they have been used in various applications like water repellency, anti-static, antibacterial, gas barrier layer, UV-protective coatings, etc. [28].

Aging effect

The effect of plasma treatment on textile substrates is not permanent. Instead there is aging, that is, the surface polarity of plasma-treated material decays with storage time. This aging effect is thought to be caused by both the thermodynamically driven reorientation of induced polar functional groups into the bulk of the material to reduce the surface energy and the diffusion of polar chemical groups in the polymer matrix [43]. Aging of plasma-treated polymer surface is influenced by many parameters such as the crystallinity degree of the treated material, the plasma gas used, and the storage conditions [44–52]. Indeed, both a lower degree of crystallinity and a higher storage temperature help molecular chain to move freely and accelerate the surface rearrangement [43, 53–55]. Attempts have been made to limit aging phenomena by stabilizing the activated surface layer via cross-linking which decreases the polymer chains mobility [56].

Plasma applications to textile processing

Plasma treatments find their application in the textile field for a variety of purposes including modification of surface energy, modification of surface topography, improvement of adhesion, and surface cleaning. This section summarizes a large number of academic research efforts on functionalizing textiles using plasma treatment methods. The number of applications presented here is neither complete nor exhaustive but merely a sample of applications that demonstrates the usefulness and possible applications of LTP technology to textile processing.

Enhancement of hydrophilic properties

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, evaluation of the wettability of plasma-treated surfaces is usually done by indirect methods such as wetting time and wicking [57].

Natural materials

Karahan and Ozdogan [8] studied raw cotton fabric treatment in DBD plasma using air and argon gases. They found that the hydrophilicity and the wickability of plasma-treated samples increased considerably and that argon plasma treatment 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. Similarly, Bhat et al. [58] observed a substantial increase in the wettability and wickability of grey cotton fabrics after atmospheric air plasma treatment. This effect was attributed to the introduction of polar groups due to the air plasma. Lam et al. [59] reported that oxygen plasma treatment significantly improved hydrophilicity of cotton fabric, leading to enhanced effectiveness of post-finishing processes. Inbakumar et al. [60] highlighted that cotton fabrics exposed to low-pressure DC glow discharge in argon showed a significant increase in wicking behavior, which was directly proportional to treatment time, discharge power, and pressure. Cai and Qui [61] found that both air/helium and oxygen/helium atmospheric plasma treatments decreased the water contact angle of wool fibers from 132.4° to almost

0° and enhanced initial dyeing rate, in the case of acid dyeing. However, the oxygen/helium-treated samples absorbed water more quickly than the air/helium-treated ones. This result was probably due to the larger concentration 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 Xu et al. [62] and Naebe et al. [63].

Regenerated materials

Vrabic et al. [64] performed a low-pressure argon plasma treatment of viscose fibers resulting in significant improvements in wettability and water retention. This result was attributed to the formation of new functional groups on the fiber surfaces and the changes in surface morphology. Zemljic et al. [21] showed that low-pressure oxygen plasma treatment decreased the water contact angle of viscose fabric from 66° to about 15° and increased the ability of the fabric to adsorb chitosan, resulting in an improved antimicrobial activity. Also, it was found that aging up to 96 h did not significantly change the contact angle (Fig. 1). Similar results, using viscose fabric treated by DBD air plasma, were reported by Kramar et al. [65]. Therefore, plasma treatment could increase the adsorption ability of viscose fibers and make them more accessible to chemicals used in the finishing processes. Persin et al. [66] compared the effects of standard chemical pre-treatment procedures and low-pressure oxygen plasma treatment on the surface properties and adsorption characteristics of viscose, modal, and lyocell fabrics. They observed that the water contact angle decreased only by 24 % (61°) after standard chemical treatments, while it decreased by 70 % (20°) after plasma treatment. The authors concluded that the oxygen activation treatment had the greatest influence on the surface energy as well as on polarity of the regenerated cellulose fabrics.

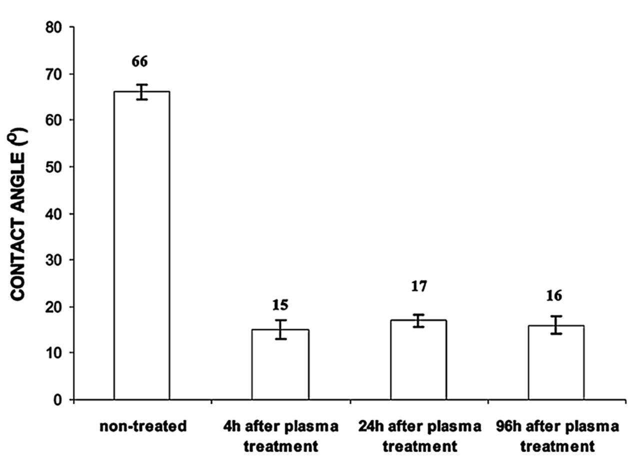


Fig. 1 Water contact angles on non-treated and oxygen plasma-treated viscose fabric samples as a function of aging "Reproduced form [21] with permission from American Chemical Society"

Synthetic materials

Effect of fiber nature McCord et al. [67] investigated the effect of atmospheric-pressure He and He/O_2 plasma treatments on polypropylene (PP) and polyamide (PA) fabrics and found that PP fabric achieved better hydrophilicity than the PA fabric. In fact, X-ray photoelectron spectroscopy (XPS) analysis showed that the surface oxygen and nitrogen content of the PP fabric increased significantly after treatment in both He and He/O_2 plasmas, whereas there was a very slight difference in the surface elemental composition of the nylon-treated and control groups. The authors suggested that the methyl group on the PP polymer appeared to be highly susceptible to bond cleavage, and might be replaced by other functional groups including carboxyl, carbonyl, and hydroxyl groups. Ferreira et al. [68] highlighted that atmospheric-pressure air plasma treatments significantly enhanced the hydrophilicity of PET and polylactide (PLA) nonwovens and that PLA seemed to be easily treated than PET. This finding was explained by the fact that more oxidized polar groups were created during plasma treatment because PLA had smaller repetition unit than PET so more ester bonds to break and oxidize. Morent et al. [69] showed that medium-pressure DBD plasma treatments of PP and PET nonwoven fabrics using different gases namely air, helium, and argon resulted in a higher wettability for the PET nonwovens compared to the PP nonwovens. An aging study revealed that the loss in wettability during storage was much higher for the PET nonwovens than for the PP nonwovens. Thus, it can be concluded that the degree of plasma-induced hydrophilization is highly dependent on the nature of fibers.

Effect of material structure Leroux et al. [6, 70] investigated the effects of atmospheric-pressure air plasma treatments on various PET materials 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 (Fig. 2). Also, it was observed that the water capillarity considerably increased from 20 to 80 % for the woven fabric and from almost 0 to 30–50 % for the nonwoven fabrics. The enhanced wettability was attributed to the introduction of hydroxyl and carboxyl groups on the PET fiber surface, as revealed by the XPS analysis. The authors concluded that the atmospheric-pressure air plasma treatment had to be set up depending on both the effect needed and the material structure.

Hossain et al. [71] showed that RF low-pressure plasma treatments using oxygen-containing gaseous mixtures (Ar/O_2, He/O_2) significantly improved the wettability of PET

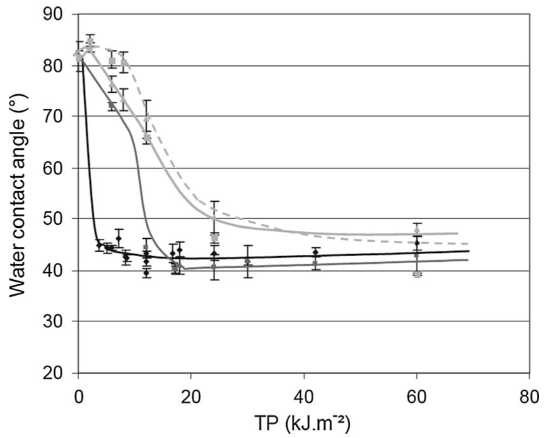


Fig. 2 Water contact angle at the PET material surfaces plotted against plasma treatment power (TP). PET film (*black line*), woven fabric (*dark gray line*), nonwoven fabrics: 70 g/m^2 (*pale gray line*), 30 g/m^2 (*dashed line*) "Reproduced from [70] with permission from Elsevier"

textile fabrics with varying construction and yarn type. In addition, they found that the 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 in the looser structured fabrics, the reactive gas particles easily moved into inter-yarn and inter-fiber spaces and caused deeper penetration of plasma surface modification into the fabrics, resulting in improved wettability or capillarity. The authors suggested that both the weave construction and the yarn type were two important parameters, in addition to pressure, power, and exposure time, since they could affect plasma treatment results in a significant way. Jelil et al. [72] investigated the effect of plasma processing parameters and fabric features on fiber surface modification by atmospheric-pressure air DBD plasma. They used a fuzzy sensitivity variation criterion for selecting a small set of fabric features relevant to plasma process and found that the degree of plasma-induced hydrophilization depended not only on plasma parameters (electrical power, treatment speed) and fabric composition, but also on air permeability, fiber count, weave construction, and summit density. Indeed, air permeability was related to the flow of plasma gas around and through the textile structure during plasma treatment. The experimental results showed that the lower the air permeability, the lower the treatment power (TP) related to wettability. This finding was explained by the fact that when air permeability was low, the plasma had more difficulties to penetrate the material, and therefore, fibers at surface will be treated first and wettability saturation happened with lower TP values, while higher energy was needed to treat more permeable textile structures in order to obtain sufficient surface oxidation. Besides, fiber fineness, weave construction, and summit density were also important parameters since they were related to the accessible fiber surface of the textile structure for plasma treatment.

Wang et al. [34] studied the penetration depth of oxygen/helium APPJ into an eight-layer stack of woven polyester fabrics with various pore sizes. After plasma treatment, they observed that larger pore size (200 vs. 100 µm) led to a deeper penetration of the plasmas. In fact, it was found that the plasma modifying effect was able to penetrate as deep as the eighth layer of fabrics with an average pore size of 200 µm, while it was only able to diffuse through six layers of the fabrics with an average pore size of 100 µm. They concluded that larger pore size makes the reactive species less likely to collide with the fibers before they can penetrate through layers of fabrics. They also found that the surface modification effect of the plasma treatment gradually reduced as the fabric layer got deeper. This result was explained by the fact that as the layer number increased, the treatment dose decreased due to the decreased number of active plasma species that could penetrate deeply into the substrate. Therefore, fabric pore size was an important factor since it affected plasma treatment effect on each layer and its penetration depth into the textile. In another study [73], the same authors investigated the influence of helium/oxygen APPJ treatment time on the penetration depth of the plasma surface modification into a four-layer stack of polyester woven fabrics. They observed that the water absorption time for the top and the bottom sides of each fabric layer was reduced from 200 s to almost 0 s and that the capillarity flow height for each fabric layer in the stack increased linearly with the increasing treatment time, but the rate of increasing trend decreased as the layer number increased (Fig. 3). The authors concluded that the degree and depth of penetration of surface modification effect depended on the penetration of active species in plasma jet, which is affected by plasma parameters (treatment time, power, gas temperature, jet-to-substrate distance) and materials structure (number of twisting, pore size) [33].

Effect of aging Takke et al. [9] showed that atmospheric-pressure air plasma treatment markedly improved the wettability and capillarity of PET woven fabric. The effect of aging at room temperature and pressure in the presence and absence of daylight was also studied (Fig. 4). In absence of light, there was a very little change in water contact angle over the 30 days following the treatment. However, in the presence of light, a substantial increase in the water contact angle (from 45° to 73°) was observed and decrease in the capillarity weight. The authors supposed that the degradation of peroxide radicals due to UV rays of the daylight could be a major factor in increasing the water contact angle of the plasma-treated fabric.

Kabajev et al. [74] reported that glow discharge plasmas operating in air, oxygen, and helium induced a substantial

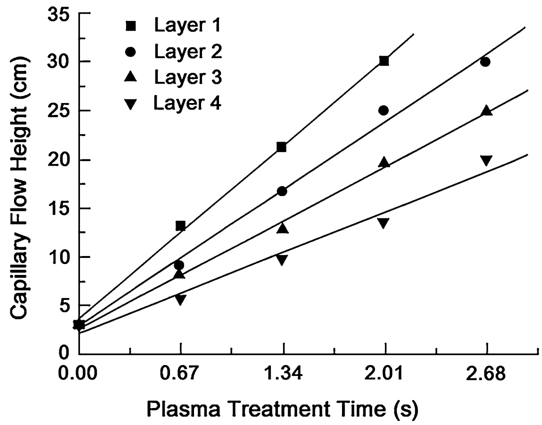


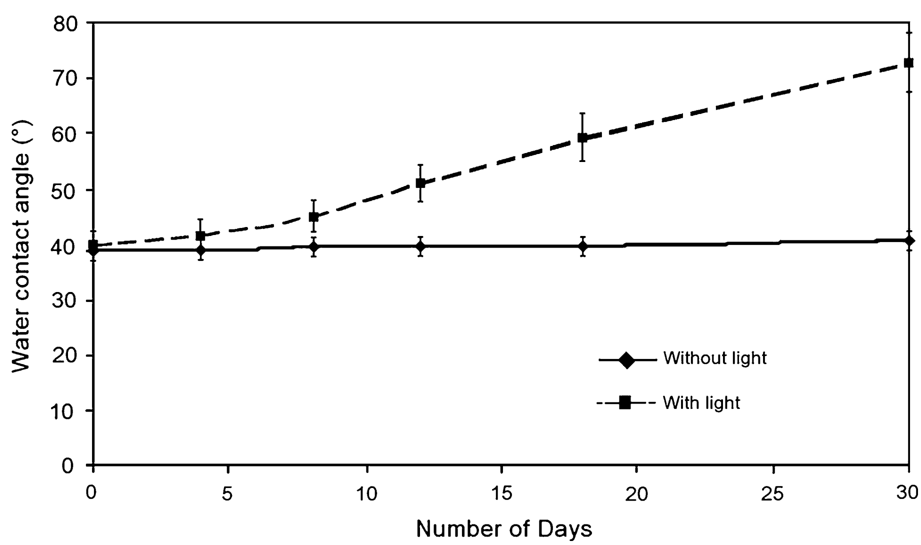
Fig. 3 Influence of plasma treatment time on the penetration of hydrophilising effect expressed by capillary flow height in 30 min for different fabric layers "Reproduced from [34] with permission from Elsevier"

increase in the capillarity of PET fabrics and that the treatment effect was stable for several days. However, no indication was given of whether aging was performed in the absence or presence of daylight. Samanta et al. [75, 76] highlighted that APGD plasma treatment using different gases namely oxygen, argon, air, and helium significantly enhanced the fluid (hydrophilic or hydrophobic) absorbency and surface energy of both nylon and PET fabrics. The enhanced absorbency was explained on the basis of combined effects of improvement in hydrophilicity and enhancement of capillary action on the fabric surface. Moreover, it was found that the plasma-induced surface modification remained stable even after 25 days for nylon fabric, while it decreased slowly during the storage period for PET fabric. Zhang and Fang [77] concluded that the aging behavior of plasma surface modification had a significant influence on the ink-jet printing property of PET woven fabric. They suggested that the modified fabrics should be printed within 24 h after treatment in order to get fresher color and better antibleeding properties.

Effect of exposure time and plasma power Shin et al. [7, 78] treated PET nonwoven fabric with an oxygen/helium atmospheric-pressure plasma and observed that the wettability increased as the treatment time increased (Fig. 5). Furthermore, XPS analysis revealed an increase in the O_{1s}/C_{1s} atomic concentration ratio progressively from 0.37 to 0.46 as plasma exposure was increased, which indicated a higher level of oxygen-based functional groups on the PET fabric surface. This effect would result in faster water spreading over the treated fabric.

Hwang et al. [79] treated PP nonwoven fabric with APGD of helium and observed that the water contact angle decreased with increasing the treatment duration. XPS analysis showed that the oxygen content (O_{1s}) and the oxygen-to-carbon ratio increased, respectively, from 0.7 to 12.7 % and 0.01 to 0.15 after plasma treatment for 120 s. The authors noticed that longer exposure time could induce more hydrophilic functional groups on the fabric surface due to the longer duration of the chemical interaction of plasma and PP, which would result in a higher wettability than the shorter plasma treatment. De Geyter et al. [80] treated PET nonwoven fabric with a DBD operating in air at medium-pressure and found that increasing electrical power and/or treatment time resulted in higher hydrophilic character of the treated fabric. The enhanced hydrophilicity was caused by the formation of oxygen-containing polar groups (O–C=O groups and C=O groups) on the PET fiber surface, as revealed by the results of XPS analysis. Similar results, using PP nonwoven fabrics treated with low-pressure oxygen plasma, were reported by Armagan et al. [81].

Fig. 4 Variation of water contact angle of plasma-treated PET samples with time, in the absence and presence of light "Reproduced from [9] with permission from John Wiley and Sons"



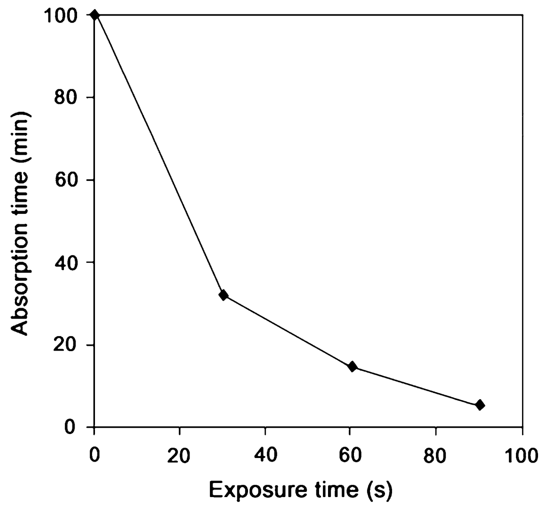


Fig. 5 Wettability change with exposure time "Reproduced from [7] with permission from John Wiley and Sons"

Effect of gas composition Morent et al. [69] treated PET and PP nonwoven fabrics by medium-pressure DBD plasma using different gases namely air, helium, and argon. They found that air plasma was more efficient in incorporating oxygen functionalities on the textile surface than argon plasma, which was more efficient than helium plasma. The high-efficiency of air plasma treatment was attributed to the fast reaction between the radicals on the textile surface and the oxygen species present in the discharge. The aging behavior of the plasma-treated fabrics after storage in air was also studied. It was found that the aging effect was the smallest for the argon plasma-treated fabrics, followed by the helium plasma-treated fabrics, while the air plasma-treated fabrics showed the largest aging effect. This result was explained by the fact that argon and helium plasma treatments of the nonwoven fabrics led to cross-linked textile surfaces, resulting in a smaller aging effect. However, air plasma-treated fabrics were not cross-linked, resulting in the highest fraction of mobile groups and the most pronounced aging effect. The authors assumed that the used argon plasma contained more ions than the used helium plasma. As a result, the argon plasma was able to create more radicals at the textile surface, resulting in a higher degree of cross-linking and a faster incorporation of oxygen-containing groups. Similar results were observed by Yaman et al. [82]. Hossain et al. [83] treated PET fabrics by low-pressure RF plasmas with air, CO_2, water vapor as well as Ar/O_2 and He/O_2 mixtures. They found that oxygen-containing plasmas (mixtures of Ar or He with O_2) achieved better hydrophilization effect within PET fabric compared to air, CO_2, and water-vapor plasmas. This result was explained by the fact that addition of oxygen to Ar or He yielded more excited species in the plasma zone, such as long-living He* and Ar* meta-stables and long-living O atoms, which were able to penetrate into textile structures. The authors concluded that the gas selection took priority over other parameters regarding the plasma penetration into the heterogeneous textile structure. Da Silva et al. [84] studied the surface modification of PET fabrics by low-pressure plasma using three different gaseous atmospheres with mixtures of argon, nitrogen, and/or oxygen ($Ar + N_2$; $N_2 + O_2$; $Ar + N_2 + O_2$). They found that PET samples treated with $Ar + N_2$ plasma exhibited higher wicking rates. This result was attributed to the increase in the –CO– and –COO– groups and decrease in the C–C and CH groups as well as higher count of nitrogen and also an almost complete reduction of silicon, as revealed by the XPS analysis. Thus, it can be concluded that the gas composition had a significant influence on the plasma modification of textile fabrics.

Effect of fiber count Wei et al. [85] treated needle-punched and meltblown PP nonwovens by oxygen cold-plasma and observed that the meltblown plasma-treated nonwoven exhibited better water adsorption properties than the needle-punched plasma-treated material. The authors attributed this result to the microfibers in the meltblown nonwoven. In fact, microfibers form more pores with smaller sizes, which enhance the capillary effect of the material. Jelil et al. [72] found that atmospheric air plasma treatment induced better hydrophilization effect for micro-PET fabrics than for regular PET fabrics. This finding was attributed to fiber fineness, which is related to the total surface area accessible for plasma treatment. Indeed, while using the same fiber content, a reduction in fiber diameter yielded higher total surface area on the fabric and, thus, greater possibilities for plasma active species to interact with fibers present at the surface and inside the woven structure. This resulted in a larger number of polar groups on the micro-PET fiber surfaces, which could explain their better wetting properties. The authors concluded that the fiber fineness influenced the water absorption behavior of plasma-treated textile materials. Tang et al. [86] treated PP nonwoven fabrics by low-temperature oxygen plasma and found that fabric with larger specific surface area achieved higher water absorption capability.

Effect of fiber surface morphology and surface purity Ren et al. [87] investigated the influence of fiber surface morphology on the hydrophilicity modification of PP nonwoven fabrics by low-temperature oxygen plasma. They found that PP nonwoven fabric made from fibers with smooth surfaces showed a much faster hydrophobic recovery than that made from fibers with rough surfaces. The authors pointed out that the fiber surface morphology of PP nonwoven fabrics was a crucial factor for long-term hydrophilicity improvement after plasma treatment. Verschuren et al. [88] studied the effect of fiber surface purity on wicking properties of PET and meta-aramid nonwoven fabrics after oxygen plasma treatment at reduced-pressure. They observed that the presence of fiber surface additives had a profound influence on the efficiency of the plasma treatment. In fact, when the layer of surface additives was plasma treated rather than the polymer surface, the treatment effect is easily washed away. However, when the sample surface was pre-cleaned before plasma treatment, this resulted in a better stability of the plasma treatment effect to water. Therefore, it can be drawn that the efficiency of plasma hydrophilization of textile materials is highly influenced by fiber surface cleanliness.

Hydrophobic functionalization

The manufacturing of water-resistant fabrics has long been an interesting subject attracting a great deal of research. Plasma treatment can be used to create a hydrophobic coating that does not significantly affect the original characteristics of the fabric, such as breathability and hand feel, but does confer to the surface a very low surface energy, which makes the fabric water-repellent or dirt-repellent. In this case, gases containing fluorine like CF_4, hexafluoroethane (C_2F_6), C_3F_6, sulfur hexafluoride (SF_6), and silane (SiH_4) are used.

Natural materials

Hocker [89] reported that hexamethyldisiloxane (HMDSO) plasma treatment of cotton fabrics using oxygen gas induced an increase in the water contact angle up to 130°, ensuring in this way a strong hydrophobic effect. Similar results were reported by Kale et al. [90]. It was observed that the water repellant properties were improved after plasma treatment. Parida et al. [91] showed that styrene/helium glow plasma at atmospheric-pressure could impart durable hydrophobic functionality to cotton textile fabric even after rigorous washing treatment. This finding was attributed to direct chemical reaction between styrene fragments and cellulose molecules of cotton fabric. Moreover, it was found that lower frequency and lower discharge voltage were necessary to control the degree of fragmentation of styrene in order to obtain high degree of hydrophobicity. Similarly, other studies [92–95] highlighted that SF_6 plasma treatments significantly enhanced the hydrophobic nature of cotton, silk, and mixed cotton-silk woven fabrics and that the imparted hydrophobicity appeared to be durable as long as the fabric was not washed [95]. This result was attributed to both surface etching and surface fluorination of the fabric fibers confirmed by X-ray photoelectron analysis. Tsoi et al. [96] showed that atmospheric-pressure oxygen plasma was capable of inducing hydrophobic modification of cotton woven fabric by using the aging effect. Fourier Transform Infrared Spectroscopy studies revealed that upon aging, the surface polarity was reversed by the formation of hydrophobic aliphatic hydrocarbons on the polymer surface. They also found that the oxygen plasma-modified cotton fabric achieved a rating similar to commercial water-repellent agents. The authors concluded that oxygen plasma treatment could provide an alternative way of imparting hydrophobicity to cotton fibers in an environmentally friendly manner.

Regenerated materials

Samanta et al. [97] studied the hydrophobic finishing of viscose fabric using He/1,3-butadiene (BD) plasma at atmospheric-pressure. After 12 min of plasma treatment, they observed that the hydrophilic surface of viscose substrate turned into highly hydrophobic surface showing water drop disappearance time higher than 60 min and water contact angle of 142°. The treatment was found to be durable to soap washing. These results were attributed to chemical reaction of butadiene with the cellulosic substrate. The authors concluded that LTP could be effectively used for carrying out reaction of 1,3-butadiene to produce durable hydrophobic finishes for cellulosic textile substrates. Similar results, using viscose fabric treated with He/dodecyl acrylate (DA) atmospheric-pressure plasma at low-frequency, were reported by Panda et al. [98]. In addition, the effect of various parameters such as concentration of precursor, helium flow rate, discharge voltage, discharge frequency, and treatment time was investigated. It was found that the plasma characteristics were correlated with hydrophobic functionalization at different treatment parameters.

Synthetic materials

Kale et al. [90] showed that HMDSO plasma improved the water-repellent properties of polyester fabric. This result might be attributed to the deposition of Si–O and Si–CH_3 groups on the surface of the treated samples, as revealed by FTIR spectroscopic analysis. Supasai et al. [93] and Paosawatyanyong et al. [99] observed a dramatic improvement in the hydrophobicity of polyethylene terephthalate fabrics with the application of SF_6 plasma treatment. In fact, the water droplet was instantly absorbed into the untreated fabric while stayed unabsorbed on the treated fabric surface (Fig. 6) [93]. The change of fabric hydrophobicity was attributed to both surface etching and deposition of C-F residue on the fabric fibers. In fact, the optical emission spectroscopy results showed spectrum lines of F I (excited fluorine) in SF_6 plasma, which was believed to be the source of hydrogen abstraction and attached with carbon composite in the fiber leading to C–F bonds. This result was in good agreement with XPS measurement which

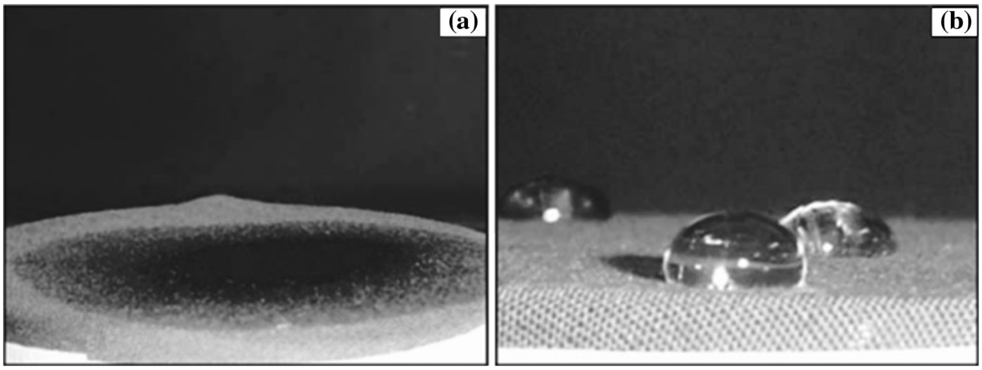


Fig. 6 The PET sample **a** before and **b** after the SF_6 plasma treatment "Reproduced from [93] with permission from Jurnal Fizik Malaysia"

revealed an increase in the intensity of the F 1 s peaks on sample surface after SF_6 plasma treatment.

Leroux et al. [100] reported that atmospheric-pressure plasma treatments with fluoropolymer aerosol dispersion atomizing improved the hydrophobic properties of polyester woven fabrics. XPS analysis proved that after the treatment, a fluorine film is grafted at the fiber surface. Similar results, using nylon fabrics treated with fluorocarbon plasmas (CF_4, C_2F_4, C_3F_6, and C_6F_{14}), were reported by Iriyama et al. [101]. However, it was found that the durability of water repellency after 30 min washing was better in fabrics treated with saturated fluorocarbon plasmas than unsaturated. This finding was explained by the fact that saturated fluorocarbon plasmas introduced longer chains of polymer on fabric surface, leading to better hydrophobicity and durability.

Modification of surface topography

As well as altering the surface chemistry of textiles, plasma treatments can modify their surface topography. This is due to the ballistic bombardment of the textile surface by energetic plasma species, which can result in heating and/or removing molecules from the material surface.

Natural materials

Karahan et al. [8, 102] observed that LTP treatment caused micro-cracks and tiny groves on cotton fabric surface because of the etching effect. Also, it was found that the argon plasma treatment was more effective than the air plasma treatment. In fact, the argon plasma-treated cotton fiber had more groves than the air plasma-treated one because of the higher etching tendency of argon gas. Radetic et al. [103] reported that both low-pressure RF plasma and corona treatment affected the surface morphology of denim fabrics. However, it was observed that the formation of pits and striations on the fiber surface was more prominent after low RF plasma compared to corona treatment. This finding was attributed to a high voltage drop in the sheath of the RF plasma and a smaller number of collisions under low-pressure conditions. Hodak et al. [94] observed that the root-mean-square surface roughness of silk fibers increased from about 10 to 30 nm upon SF_6 plasma treatment. This finding was attributed to both etching process by high energy species generated in SF_6 plasma and deposition of materials on the sample surface. Kan et al. [104] highlighted that low-pressure oxygen plasma treatment increased the surface roughness of wool fibers probably due to the etching effect on the fiber surface. Indeed, SEM revealed obvious grooves appearing uniformly along the direction of the fiber axis on the surface. Moreover, the fiber-to-fiber friction measurements showed that the LTP treatment reduced the directional frictional effect of wool fibers, which might thus provide an anti-felting effect to the wool fibers [105, 106]. Kulyk et al. [107] showed that DBD treatment in atmospheric air affected the wool fiber edges and increased the roughness of the scales surface (Fig. 7). This effect might help to eliminate the hydrophobic surface barrier of the wool fiber, and hence, more chances would be provided for the chemicals such as dyestuff to enter into the wool fabric.

Goud [108] treated wool woven fabric with atmospheric air DBD plasma and observed that the induced surface morphology changes were dependent on plasma processing parameters. In fact, it was found that the etching effect of active species in plasma over the wool substrate was directly proportional to the applied voltage and inversely proportional to the inter-electrode spacing. This result was explained by the fact that as the electrode spacing was reduced and/or the voltage across electrode was increased, the ratio of active gas species to the total gas species would be higher, which would give intense treatment to fiber surface and, thus, resulting in higher fiber roughening.

Wong et al. [109] treated linen fibers by low-temperature oxygen and argon plasmas at various discharge power

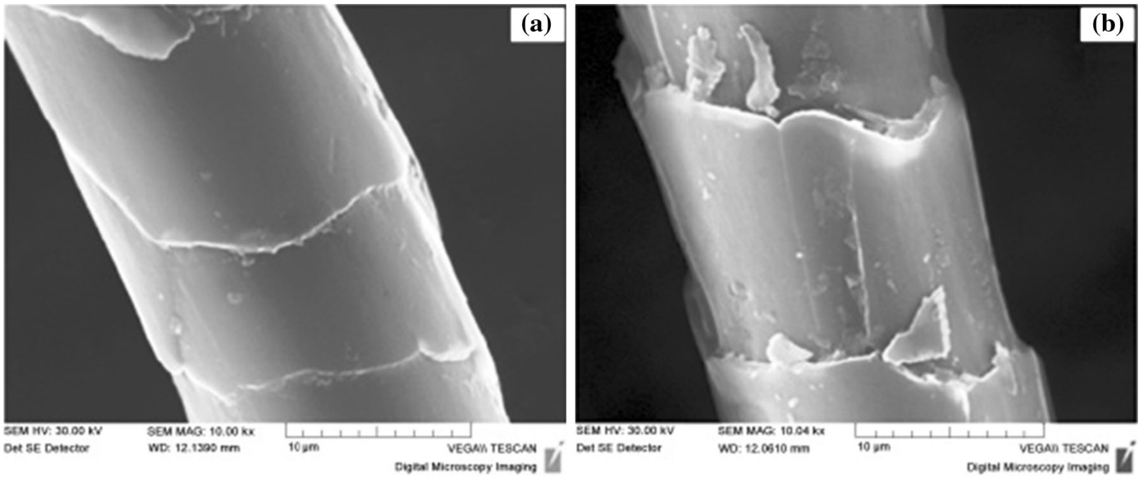


Fig. 7 The characteristic of **a** untreated washed wool fiber and **b** washed wool fiber after the DBD treatment at maximum energy level "Reproduced from [107] with permission from AUTEX"

levels and exposure times. SEM studies showed that the fiber surfaces were roughened by plasma treatment and in some cases voids and cracks were also observed, especially after oxygen plasma ablation. Also, it was observed that the voids and cracks became more pronounced as exposure time increased. Other research groups [110–112] found that both oxygen and argon low-pressure plasma treatments notably roughened the surface of silk and jute fibers and that the induced surface roughness increased with plasma treatment time. This finding was attributed to the physical sputtering and chemical etching effect of LTP treatment [112].

Regenerated materials

Kan and Yuen [113] treated Tencel and viscose rayon fibers with LTP using oxygen gas. SEM revealed the formation of ripple-like structures oriented in a direction perpendicular to the fiber axis. Increasing the plasma treatment time led to more distinct ripple-like structures on the fiber surface. Vesel et al. [10] treated viscose fabrics with RF oxygen, nitrogen, and hydrogen plasmas for 5 s. SEM analysis results showed that the fibers' surface treated in nitrogen plasma was similar to the untreated surface, while after treatment in hydrogen or oxygen plasma, the surface became rougher. Kramar et al. [65] reported that DBD air plasma treatment of viscose fibers induced defects in the fiber surfaces and micro-cracks were observed on the air plasma-treated fiber surfaces due to plasma etching.

Synthetic material

Costa et al. [113] showed that plasma treatment using different gaseous atmospheres caused alterations in the morphology of PET fibers, with the formation of fissures and pores. They also found that induced surface roughness depended on the gas composition of the plasma. In fact, SEM observations revealed that samples treated with atmosphere of $O_{10}N_{83}H_7$ and $N_{92}H_8$ showed more morphological changes on their surface than the samples treated with an atmosphere of $O_{90}N_9H_1$. Zhongfu et al. [114] treated PET fibers by low-pressure argon/oxygen plasma for 1 min and observed that the smooth and glossy surface of PET fiber was roughened by etching (Fig. 8). Yip et al. [115] found that LTP treatment using different nonpolymerizing gases namely, oxygen, argon, and CF_4 affected the surface morphology of nylon fibers and that oxygen plasma gave more distinct effects than argon plasma. This result can be explained by the fact that argon is an inert gas and its plasma generally induces relatively low etching rates compared to oxygen plasmas which are known to be very reactive etchants. On the other hand, it was found that CF_4 plasma produced less destructive effects on the nylon fabrics.

Samanta et al. [76] treated nylon and PET fabrics with atmospheric plasma using various gases namely, oxygen, argon, air, and helium and found that the increase in surface roughness was more pronounced for the nylon fabric compared to the PET fabric. This result was attributed to differences in the physical properties and crystallinity of the two fabrics. Therefore, the impact of a plasma treatment must depend on the polymer nature. Wang et al. [34, 73] showed that exposing multiple-layer stack of woven PET fabrics to a helium/oxygen atmospheric-pressure plasma caused micro-pits whose density, depth, and size decreased with increasing fabric layers. In fact, the top few fabric layers had more surface etching while the bottom few layers had little etching. This finding indicated that the active plasma species mainly reacted with the substrate surface in the first few layers.

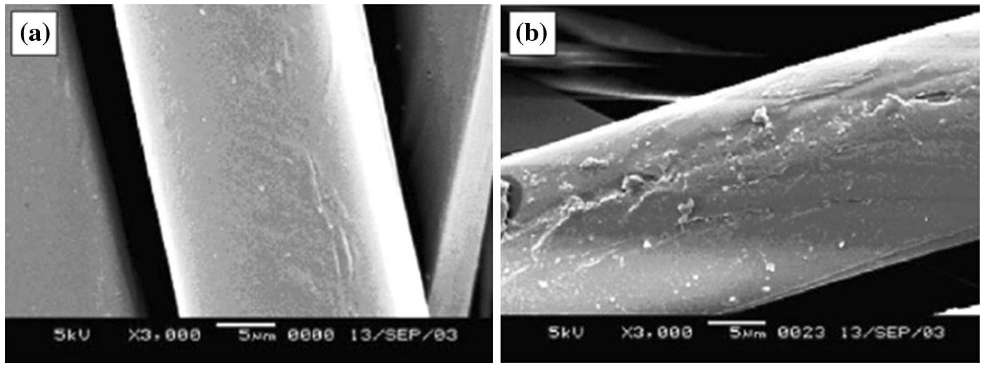


Fig. 8 Scanning electron micrograph of polyester fiber: **a** untreated and **b** treated "Reproduced from [114] with permission from SAGE Publications"

Adhesion enhancement

As shown above, plasma treatments can be effectively used to increase the surface energy, the wettability, and the surface roughness of textile materials. These potential effects promote adhesion between textile substrates and adhesives that cannot be used without surface treatment and, thus, leading to improved material properties.

Natural materials

Garg et al. [116] showed that APGD pre-treatment of wool fabric improved the ability of the substrate to bond with an anthraquinone-2-sulfonic acid doped conducting poly-pyrrole coating. The improved fastness of the coating was attributed to the formation of bonding sites on the epiticule surface by the plasma treatment. Vasiljevic et al. [117] reported that low-pressure water-vapor plasma pre-treatment increased the effective concentration of fluoroalkyl-functional siloxane (FAS) network on cellulose fibers, which will concurrently increase the adhesion of the FAS coating and improve its washing fastness. Oliveira et al. [118] studied the adhesion of phase-change material (PCM) microcapsules applied by a padding process in a wool fabric after it was treated with air DBD plasma. They found that plasma treatment greatly enhanced the adhesion of PCM microcapsules on the surface of the wool fiber, even after several washing cycles. The authors concluded that DBD plasma treatment can be considered as an excellent solution for promoting the functional performance of textile products finished with PCM microcapsules, achieving more durable properties, and so contributing to the sustainability of innovative textiles. Bozaci et al. [119] treated flax fibers with argon and air atmospheric-pressure plasmas under various plasma powers to improve interfacial adhesion between the flax fibers and high density polyethylene (HDPE) and unsaturated polyester. They found that the interfacial adhesion of argon plasma-treated flax fibers and HDPE matrix was superior to those of air-treated and untreated flax fiber. In addition, it was observed that the interfacial adhesion was further enhanced by increasing plasma power. This result might be attributed to the increasing of roughness and the introduction of polar functional groups onto flax fiber surfaces, as indicated by XPS and SEM measurements.

Regenerated materials

Felix et al. [120] reported that oxygen plasma treatment considerably enhanced the interfacial adhesion between regenerated cellulose fibers (rayon) and a polyethylene (PE) matrix, as established by the measured shear strength values and the birefringence patterns observed. The improved adhesion was attributed to covalent bonds formed between the rayon fibers and the matrix. In addition, it was found that longer plasma treatment times resulted in a significant improvement of the fiber-matrix adhesion. Cho et al. [121] reported that oxygen plasma treatment enhanced the adhesion between lyocell fibers and plated metal and improved the electrical conductivity, even after abrasion and washing tests. Graupner et al. [122] investigated the influence of different plasma treatments on the interfacial adhesion between lyocell fibers and a poly(lactic acid) polymer matrix. They found that the best improvement of the fiber/matrix adhesion was obtained by a plasma treatment with a mixture of water vapor and ethylene resulting in an interfacial shear strength of 17.8 N/mm^2 in comparison to the untreated lyocell fiber with 10.3 N/mm^2. Therefore, it can be concluded that plasma technology is a good alternative to conventional wet-chemical methods to improve the adhesion properties of regenerated cellulose textile materials.

Synthetic materials

Leroux et al. [70] showed that atmospheric-pressure air plasma treatment significantly improved the adhesion between PET fabrics and silicon resin containing adhesive primer. The enhanced adhesion was ascribed to chemical interactions between the plasma-treated PET fibers and the silicon resin. Wang et al. [123] reported that atmospheric-pressure helium plasma treatments increased the interfacial shear strength (IFSS) of UHMPE fibers by 57–139 % compared to untreated specimen. SEM and XPS analysis revealed that plasma treatment increased the roughness of the fiber surfaces and introduced oxygen-containing functional groups onto the surfaces, and thus leading to improved adhesion between the fibers and the epoxy resin. In addition, it was shown that lower plasma power and higher treatment head temperature resulted in the best improvement. Rahel et al. [124] highlighted that atmospheric-pressure nitrogen plasma resulted in an eightfold increase in adhesive strength between PET monofilament surface and an epoxy resin matrix, without any change in mechanical properties of the monofilaments. The improved adhesive strength was attributed to polar group interactions. Cernakova et al. [125] found that pretreating a nonwoven fabric with atmospheric-pressure air plasma enhanced the uniformity of a subsequent nanostructured Fe_2O_3 layer. It was also found that the Fe_2O_3 coating exhibited good stability and a remarkable wash resistance. Armagan et al. [126] showed that the adhesion bond strength of argon plasma-treated laminated PP samples improved by up to 150 % compared to untreated laminated fabrics and that a longer plasma treatment time was more effective in improving the adhesion than increasing the plasma power. The increased adhesion strength of laminated fabrics might be attributed to the increase in surface roughness due to argon plasma treatment, as revealed by SEM observations. Huang et al. [127] investigated the effect of argon plasma on surface modification of ultra-high molecular weight polyethylene (UHMWPE) textile. The obtained results showed that the peel strength of UHMWPE textile/adhesive (PU_T01) composites was increased from 0.6 into 4.6 kgf/in after argon plasma treatment at 40 w for 5 min. Liu et al. [128] investigated the influence of moisture regain on the effectiveness of atmospheric-pressure plasma treatment on the IFSS of aramid fibers to epoxy. They found that the IFSS was not affected by the existence of moisture in the fiber. Conversely, it was enhanced with increasing moisture content in the aramid fibers. This result might be attributed to the enhanced interaction between the plasma and the water molecules preexisting in the fibers during treatment. The authors concluded that moisture regain promoted the plasma treatment effect in the improvement of adhesion property of aramid fibers to epoxy.

Surface cleaning

Plasma treatment can also be used for surface cleaning and desizing of textiles. However, selectivity of the plasma for the material to be removed from the fiber surface is required, since the fiber structure itself should not be damaged.

Natural materials

Desizing through plasma treatment is a fairly recent and novel process, which is considered as an environmental friendly alternative to the conventional wet-chemical treatment. Cai et al. [129] investigated the effects of air/helium (air/He) and air/oxygen/helium (air/O_2/He) atmospheric-pressure plasmas on desizing of PVA on cotton. It was found that air/O_2/He plasma treatment seemed to be more effective than air/He plasma on PVA removal. Also, it was shown that both plasma treatments did not only serve to remove some PVA size, but also to significantly facilitate PVA removal by subsequent washing. In fact, XPS analysis showed that plasma treatment broke down PVA molecular chains into shorter lengths, which might facilitate swelling, dissolving, and dispersing of PVA. Thus, atmospheric plasma treatment might greatly increase the solubility of PVA on cotton in cold water, resulting in a higher weight loss in cold washing. In another paper [130], Cai and Qui highlighted that a 5 min air/O_2/He plasma treatment followed by one cold wash showed to be competitive with the H_2O_2 process (2 cycles of cold and hot wash), and a 8 min plasma treatment followed by one cold wash gave even better results. Similar results, using cotton fabric treated with atmospheric-pressure helium plasma, were reported by Cai et al. [131]. The authors concluded that desizing PVA size only using cold water washing after plasma treatment is feasible, offering the advantages of saving energy and wash water. Li and Qui [132] showed that He/O_2 APPJ pre-treatment facilitated blended sizes removal from cotton fabric in subsequent $NaHCO_3$ treatment and that the PDR increased with prolonging plasma exposure time (Fig. 9). Kan and Yuen [133] compared the desizing effect induced by atmospheric-pressure oxygen plasma treatment with conventional enzyme desizing treatment. They found that plasma treatment followed by an enzymatic fading process resulted in a more significant color fading effect for denim cotton fabric. Peng et al. [134] investigated the influence of moisture absorption of cotton fabrics on desizing of PVA during APPJ treatment. They found that the fabric with the lowest moisture regain (1.8 %) had the highest desizing efficacy compared to the others plasma-treated fabrics with moisture regain of 7.3 and 28.4 %, respectively. Indeed, the PDR reached 96 % after 64 s exposure time. When this was followed by 20 min hot washing, the plasma-treated sample was shown by SEM to be as clean as the unsized sample.

Regenerated materials

Cai et al. [135] showed that atmospheric-pressure air/He and air/O_2/He plasma treatments were able to remove some of the PVA on rayon (viscose) fabric and increase cold water

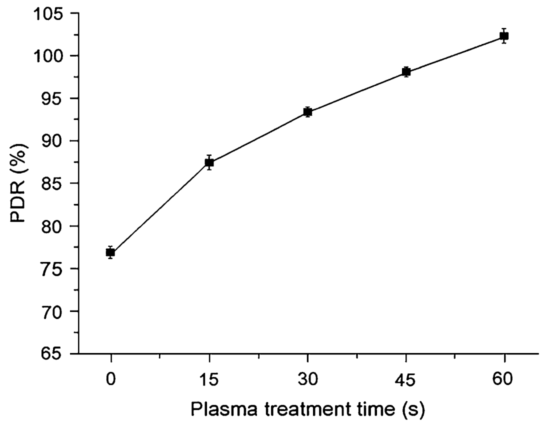


Fig. 9 Influence of plasma treatment time on the PDR of cotton fabric sized with blended sizes (concentration of $NaHCO_3$: 5 g/l; desizing temperature: 80 °C; desizing time: 20 min) "Reproduced from [132] with permission from Elsevier"

solubility of PVA remaining on the surface, resulting in a higher weight loss in cold washing without negatively affecting the bulk substrate properties. This weight loss became greater as the plasma treatment time increased. In addition, it was shown that plasma treatment followed by one cold wash and one hot washing was as effective as traditional chemical desizing followed by two cycles of cold and hot washing. In fact, a PDR of 93.36 % was attained for a sample treated with air/O_2/He plasma for 5 min and only a cold washing. The authors concluded that the application of the atmospheric plasma treatment in the desizing of PVA provides an alternative approach that decreases the consumption of energy and water and eliminates the chemicals involved in conventional desizing processes.

Synthetic fibers

Bae et al. [136] reported that oxygen plasma treatment efficiently removed sizing agents such as PVA, polyacrylic acid esters, and their mixture from PET fabrics. Li and Qui [137] compared He/O_2 APPJ plasma-aided desizing with conventional wet desizing of polyacrylate on PET fabrics and found that plasma treatment significantly reduced desizing time. Indeed, SEM analysis revealed that the PET fiber surfaces were as clean as unsized fibers after 35 s of plasma treatment followed by $NaHCO_3$ desizing. XPS analysis indicated that number of oxygen-based functional groups increased for the plasma-treated polyacrylate sized fabrics. In another study, Li et al. [138] showed that more than 99 % PDR was achieved after 65 s plasma treatment followed by a 5 min $NaHCO_3$ desizing. The authors highlighted that these findings clearly demonstrated the viability and ecological benefits of a plasma-aided size removal system.

Improving dyeing and printing properties

The application of plasma as a pre-treatment in textile wet processing may advantageously improve the dyeing and printing properties of textile materials. In this way, wettability and capillarity improvement, enhancement of surface area, creation of reactive sites on the fiber surfaces, and many other actions can contribute to the final effect depending on the plasma operating conditions.

Natural materials

Sun and Stylios [139] reported that low-pressure oxygen plasma treatment considerably increased the dyeing rate of wool and cotton fabrics, leading to quicker and higher exhaustion of dyestuff. This could lead to shorter processing times and a reduction in the amount of chemicals in wastewater. El-Zawahry et al. [17] reported that LTP treatment resulted in an improved initial dyeing rate of wool fabric. Also, it was found that the nature of the plasma gas governed the final exhaustion percentage of the used acid dyes according to the following descending order: nitrogen plasma > nitrogen/oxygen (50/50) plasma > oxygen plasma > argon plasma > control. In addition, it was found that increasing the aging up to 100 h resulted in a slight decrease in the extent of exhaustion. Kan [140] investigated the influence of oxygen GD plasma treatment on the dyeing properties of wool fibers using three dyeing systems, namely chrome dye, acid dye, and reactive dye. They found that the dyeing rate of all three dyeing systems increased significantly, but in the case of chrome and acid dyeing, the exhaustion percentage at equilibrium did not show any significant change (Fig. 10). This finding was explained by the fact that the depth of penetration and etching caused by plasma treatment was not sufficient to alter the internal structure of the fiber or to induce any dye sites in the fiber. However, in the case of reactive dye, it was found that the final dyebath exhaustion and dye fixation on fiber were increased (Fig. 11). This result was attributed to the increase in the number of available dye sites caused by the introduction of oxygen

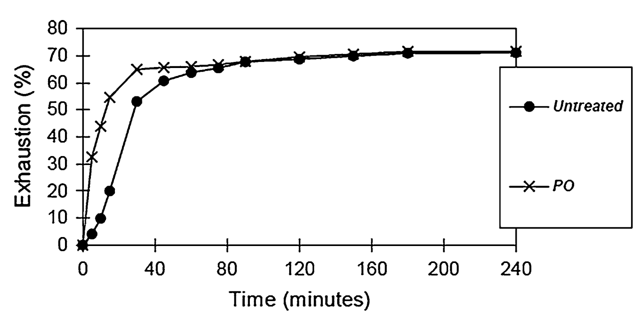


Fig. 10 Percentage of dyebath exhaustion of untreated and LTP-treated wool fibers (PO) with acid dye "Reproduced from [140] with permission from AUTEX"

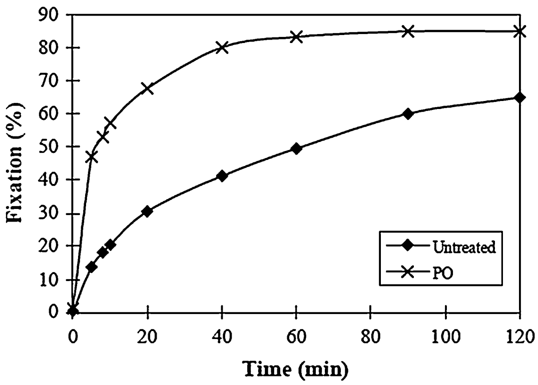


Fig. 11 Fixation curve of untreated and LTP-treated wool fibers (PO) with reactive dye "Reproduced from [140] with permission from AUTEX"

functional groups in the fiber surface. The authors concluded that LTP treatment could improve the dyeing behavior of wool fiber under different dyeing systems.

Chvalinova and Wiener [141] showed that diffusive coplanar surface barrier discharge plasma (DCSBD) at atmospheric-pressure improved the amount of acid dye absorption of wool fabrics, resulting in enhanced dyeability and printability. The authors concluded that plasma treatment of wool can in future replace wet-pre-treatment processes for wool dyeing and printing. Fang et al. [142] reported that low-temperature oxygen plasma dramatically improved the antibleeding performance of silk fabric. This result was attributed to the etching and the polar groups introduced onto the surface layer of the fabric which improved the hydrophilicity of the fabric, consequently expedited the absorption speed of the ink. The authors concluded that low-temperature oxygen plasma offers an attractive prospect to the application of inject printing of fabrics with pigments inks. Ratnapandian et al. [143] highlighted that plasma treatment and padding are a feasible combination for the continuous application of natural dyes derived from the Acacia plant family on wool. In fact, up to 30 % enhancement of dye absorption on plasma-treated wool substrate was observed as compared to untreated sample for both helium and helium/nitrogen (95/5 %) gases used. The enhanced dye uptake was attributed to sustained surface modification (etching) with plasma treatment. Also, the wash, rub, and light fastness of the dyed plasma-treated samples were evaluated, giving fair to good fastness grades.

Synthetic materials

Wang et al. [144] investigated the effect of atmospheric-pressure plasma treatment on basic dyeability of nylon 6 fibers. They observed an increase in dye diffusion rate of plasma-treated fibers, using laser scanning confocal microscope (LSCM). In addition, it was found that the dyeing intensity and penetration depth increased as the treatment time increased, indicating a high diffusion rate for longer treatment time. This result was explained by the fact that, as the plasma treatment time increased, a greater degree of etching was achieved and more polar groups such as hydroxyl and carboxyl groups produced on the surface of nylon 6 fibers, leading to a better wettability and thus a better dyeability of the fiber. The authors emphasized that LSCM may be effectively used in detecting the change of dye diffusion rate in nylon fibers due to plasma treatment. Wang and Wang [145] studied the possibility and effectiveness of applying radiofrequency oxygen plasma treatment to enhance the final color properties of the ink-jet-printed polyester fabric. They found that the antibleeding performance of the plasma-treated PET fabric was greatly improved. Yaman et al. [146] highlighted that plasma pre-treatment could further enhance the printability of textile fabrics. In fact, they observed that polyester fabric printed with pigment dyestuff after argon and air plasma had higher color intensity than those untreated fabrics printed by the same method at equal pigment color ratios. In addition, it was found that fastness of the plasma-treated samples was higher than the untreated fabrics because of improving bonding strength to the binder. Similarly, Maamoun and Ghalab [147] reported that the pre-treatment of wool and polyester (45/55) blended substrate with air plasma enhanced the K/S values by 173.6 and 68.9 % for printing with both dye mixtures Realan/Dianix and Supralan/Dianix, respectively, when compared with the untreated printed sample. The authors concluded that LTP attacked the chains on the crystalline surface and amorphous region and caused a significant change in fiber crystallinity.

Finishing

Plasma treatment with different kinds of plasma gases can impart special functionalities to textile materials such as antimicrobial, anti-shrinkage, wrinkle resistance, self-cleaning function, UV protection, flame retardancy, etc. Such effects are achieved by bringing about surface modifications at micro- or nano-scale, without affecting the bulk properties of the textiles.

Sterilization and antimicrobial properties

Textile materials are susceptible for cross-contaminations of pathogenic bacteria, which can cause several problems like strength deterioration, odor generation, and health concerns caused by microorganisms. Thus, plasma treatment can be an efficient sterilizing tool of textiles via highly energetic UV light and reactive species. Shahidi and Ghoranneviss [148] investigated the sterilization effects of low-pressure oxygen plasma on bacterial colonies in cotton fabrics. They found that plasma treatment completely sterilized the cotton fabrics inoculated with various concentrations of staphylococcus aureus. This finding was explained by the fact that UV irradiation and activated free radicals generated during plasma treatment weakened the cell wall of the microorganisms by reacting with the hydrocarbon bonds, and caused disruption of unsaturated bonds, particularly the purine and pyrimidine components of the nucleoproteins. The authors suggested that oxygen plasma can be effectively used as an alternative method for sterilizing and protecting cotton fabrics. Muller et al. [149] also studied the disinfection of cotton fabrics by dielectric barrier discharges and observed a significant reduction of microorganism population in some of the samples. In addition to sterilization, plasma treatments can also impart antimicrobial and antibacterial functionality or aid in antimicrobial finishing.

Kostic et al. [150] showed that the incorporation of sliver ions into cotton/polyester fabrics previously treated in a DBD led to the generation of antimicrobial materials having the activity against a broad spectrum of microbes (Gram-negative bacteria strains—*E. coli*, Gram-positive bacteria strains—*S. aureus*, and yeast—*C. Albicans*). Similar results, using PET fabric treated with DBD plasma and coated with chitosan by immersing in a chitosan acetate aqueous solutions, were reported by Sophonvachiraporn et al. [151]. Sahidi et al. [152] highlighted that a very good antibacterial activity was achieved after sliver plasma sputtering on the surface of cotton fabrics and that dyeing by different classes of synthetic and natural dyes did not have any negative effect on antibacterial activity of silver-coated cotton fabrics. In fact, it was found that the antibacterial efficiency of dyed sputtered samples remained constant as compared with sputtered samples without dyestuff. Malshe et al. [153] showed that atmospheric-pressure glow discharge plasma was effectively used to polymerize and graft diallyldimethylammonium chloride (DADMAC), a quaternary ammonium salt monomer, onto 50/50 nylon/cotton blend standard military fabric, which conferred a grafted polymer network of DADMAC with durable antimicrobial properties. The authors underlined that the obtained antibacterial bulk fabric could detoxify harmful microorganisms in the event of a biological warfare agent attack, and also improve the esthetic value of the garment by fighting odor creating bacteria upon prolonged wear of the uniform.

Anti-felting/shrink resistance of woolen fabrics

Felting and shrinkage are an essential issue of wool garment due to the specific scale-like, hydrophobic surface of fiber. In fact, the hydrophobic epicuticle and scale structure of the wool fiber led the individual fibers within the textile to move towards their root end under mechanical action in the wet state, thereby causing fiber entanglement and shrinkage of the wool fabric [89]. To overcome this drawback, the frictional properties of wool fibers need to be tailored. Thus, LTP can be used as an effective technique for modifying the surface properties of wool fabric, without incurring traditional issues. Kan et al. [154] highlighted that LTP could impart significant shrink-resistant and anti-felting effects to the wool fabric. This finding was attributed basically to the etching effect which reduces the differential friction coefficients of the fibers, and thus decreases the natural shrinkage tendency. The authors concluded that LTP is a viable method for modifying the wool fabric with a quite significant effect. Cai et al. [155] observed that knitted wool fabric samples pretreated with atmospheric plasma and treated with Synthappret BAP finishing agent, which is a bisulphite adduct of a polyisocyanate polyether, showed area shrinkage of 5.64 % (air/helium) and 5.23 % (oxygen/helium), respectively. However, the area shrinkage value of wool finished by Synthappret BAP without the plasma pre-treatment was 17.5 %, far above 8 %, suggesting that the finishing agent itself could not meet the "machine washable" requirement. Therefore, the atmospheric plasma treatment combined with Synthappret BAP finishing clearly produced a shrink resist effect, resulting in improved anti-felt properties of the wool fabric. Mori et al. [156] treated wool fabric using a DBD apparatus by varying the power and flow rate of air and found that shrink-proofing increased to a greater degree with the increase in the treatment time. In another study, Mori and Inagaki [157] investigated the anti-felting mechanism of argon plasma-treated wool fabric using XPS. They suggested that the intermediate cystine oxides groups, i.e., –S(O)–S– and $–S(O)_2–S–$, produced on the fiber surface during plasma treatment had a strong affinity with water. In addition, carboxyl and sulphonic acid groups generated on the fiber surface might also increase surface hydration, and thus play some part in the felting behavior of wool fiber. Subsequently, cohesive force was exerted between these groups and water molecules on the fiber surfaces and this resulted in a decrease of the flexibility of the individual fibers in assembly. This limited the unidirectional movements of the fibers and thus improved the anti-felting behavior of the wool fibers. Hence, it seems that plasma pre-treatment of wool does offer an appropriate environmentally acceptable alternative to the existing treatments using chlorine.

Wrinkle-resistant property

Cotton has poor elasticity and resilience. This is because the hydrogen bond is reformed after the force applied to the fiber. Plasma treatment can be used to enhance the resilience of cotton. Kan [158] showed that oxygen APPJ treatment followed by 0.2 % Titanuim dioxide (TiO_2)

treatment significantly enhanced the wrinkle-resistant property of cotton fabric. This finding was attributed to the etching effect on the fabric surface caused by plasma pre-treatment which provides a new pathway for the finishing agent to enter into the fiber, resulting in the formation of more crosslinkages with an increase in the wrinkle recovery angle. In another study, Kan et al. [159] reported that atmospheric plasma pre-treatment of cotton fabric further improved the application of 1,2,3,4-butanetetracarboxylic acid (BTCA) wrinkle-resistant finishing without generating adverse effect. Lam et al. [160] found that plasma treatment conditions with a 10 mm/s speed, a 0.1 L/min oxygen flow rate, and a 4 mm jet-to-substrate distance together caused a significant improvement in the wrinkle-resistant properties of the cotton fibers treated with three different BTCA treatments (5 % BTCA and 10 % sodium hypophosulfite (SPH); 5 % BTCA, 10 % SPH and 0.1 % TiO_2; 5 % BTCA, 10 % SPH and 0.2 % TiO_2). Moreover, they found that the treatment speed was the dominant factor, followed by jet-to-substrate distance and oxygen flow rate, in affecting the extent of improvement. In fact, SEM images indicated that more topographical changes occurred at the surface of the fibers implying more effective surface modification and etching effect of plasma treatment generated at slower speed (longer treatment time). The authors underlined that careful control of treatment time was important to avoid fiber damage.

Flame retardancy

Improving the flame retardant property of textiles becomes necessary to minimize the fire hazard and improve human safety under many circumstances. Thus, considerable efforts have been made to develop flame retardant textiles. Generally, the flame retardancy of textile fabrics is achieved by applying flame retardant finishes using textile finishing and coating methods. Indeed, plasma surface modification process seems to be a potentially useful technique for imparting flame retardant properties to textiles.

Raslan et al. [161] highlighted that DBD atmospheric air plasma treatment at 1.3 w for 2 min after spreading aluminum oxide (Al_2O_3) powder on polyester fabric significantly enhanced the flame retardancy. In fact, it was found that the burning time increased from 39 s for untreated sample to 50 s for sample treated with air plasma-Al_2O_3, while the burning rate decreased from 230 m/min to 180 m/min for the same sample. In addition, it was shown that the technique of spreading the powder on the sample was more effective on enhancing the fire retardant property rather than spreading it on the electrode disk. Ghoranneviss and Shahidi [162] investigated the flame retardancy of cotton fabrics pre-treated with low-pressure nitrogen plasma and then inoculated in various metallic salts. The flame retardancy of the samples was characterized by limiting oxygen index (LOI) and char yield. The obtained results showed that nitrogen plasma pre-treatment has synergistic effect on metallic salts for improving the flame retardant properties of cotton fabrics. They also found that dyeing the plasma pre-treated and inoculated cotton samples does not have any negative effect on flame retardancy. In another study [163], the same authors highlighted that nitrogen plasma treatment followed by Nanoclay treatment increased the flame retardant properties of cotton fabric. In fact, it was found that the char yield value for N_2 plasma/Nanoclay-treated cotton increased to 12 % after complete burning. Similar improvements were achieved for the LOI values. The improved flame retardancy of the treated samples was attributed to the earlier decomposition of Nanoclay to drive the char formation, which could inhibit the transmission of heat, energy, and O_2 between flame and cotton fabrics.

Ultraviolet (UV) protection

UV protection by textile fabrics has recently become a focus of great interest, particularly in connection with environmental degradation of ozone layer depletion. Indeed, textile fabrics can provide simple and convenient protection against skin damage, but not all fabrics offer sufficient UV protection. To describe the degree of UV radiation offered by clothing materials, the ultraviolet protection factor (UPF) is commonly used [164]. According to ASTM D6603, the level of protection is evaluated by good, very good, and excellent if the values of UPF are 15–24, 25–39 and >40, respectively.

Raslan et al. [161] reported that DBD atmospheric air plasma pre-treatment facilitated the deposition of TiO_2 on polyester fabric, resulting in a noticeable enhancement in the fiber protection against ultraviolet rays. In fact, it was found that the UPF increased from 8 for untreated PET fabric to 48.3 (>40) for plasma-TiO_2-treated PET sample, which means that the treated fabric has excellent protection against UV radiation. Hashemizad et al. [165] highlighted that using 0.2 % nano TiO_2 on RF oxygen plasma-modified PET fabric was enough to obtain an acceptable UV protection level even after 10th washing cycles. Ibrahim et al. [166] treated cotton/polyester (80/20), cotton/linen (50/50), and linen/viscose-polyester (50/50) fabric blends with plasma gases namely, oxygen, air, and argon. Then, the plasma pre-treatment was followed by subsequent treatment with certain metal salts (Zn-acetate, Cu-acetate, Al-chloride, and Zr-oxychloride). Their results showed that oxygen plasma treatment followed by Cu-acetate or Zn-acetate treatment gave the best UV protection for all fabrics.

Self-cleaning properties

The requirement to render the surface of textile materials “self-cleaning” or at least “easy-to-clean” is an important general issue. This effect, known also as “lotus effect,” would considerably enhance the utility value of the textiles and would improve the environment quality. Plasma pretreatments can be used to obtain self-clean effects of textile materials by the maximum increase in the water repellency, without affecting their bulk properties. Qi et al. [167] discovered that the self-cleaning properties of PET fibers, such as bacterial activities, colorant decomposition, and degradation of red wine and coffee stains, were drastically improved after modification of PET fibers with oxygen plasma and subsequent loading of TiO_2 prepared by an aqueous sol-gel process. This finding was attributed to the increased number of active sites and bondability on the plasma-treated polyester surface allowing for much higher TiO_2 loading on the textile compared to non pre-treated sample. Similar results were observed by Hashemizad et al. [165] and Baghriche et al. [168]. Mihailovic et al. [169] highlighted that oxygen and argon RF plasma-modified PET fabrics loaded with hydrophilic TiO_2 showed improved self-cleaning properties. This result was explained by the fact that plasma activation of PET fibers enhanced the deposition of colloidal TiO_2 nanoparticles onto the fiber surface resulting in an excellent photocatalytic activity. Also, it was found that oxygen plasma pretreatment proved superior to that of an argon plasma. Mejia et al. [170, 171] reported that cotton and nylon fabrics showed acceptable self-cleaning properties after RF plasma and TiO_2 treatments. This result was attributed to the plasma-induced surface roughness, leading to better interaction between TiO_2 and textile.

Asymmetric wettability

By using plasma technology, new and improved properties of textile materials can be created that cannot be achieved by standards procedures, where surface nano-structuring of natural and synthetic fibers is emphasized. Kwon et al. [172] showed that lyocell fabric subjected to 5 min of oxygen plasma etching, followed by 30 s of plasma-polymerized hexamethyldisiloxane turned into a superhydrophobic surface with a static contact angle greater than 160° and a sliding angle <2°. This finding was attributed to the oxygen plasma etching, which generates micro-scale roughness on the lyocell fabric surface. However, the backside of the fabric was protected during plasma treatment and remained hydrophilic. This was demonstrated by a water droplet immediately being absorbed and spreading out on the untreated backside, while it rolled off the treated surface, demonstrating a bouncing effect. Such extremely opposite wetting behavior was also reported by Chen et al. [173] who used an atmospheric plasma treatment (He and N_2 mixtures) to improve the surface hydrophilicity of thermoplastic polyurethane (TPU) nonwoven while retaining the hydrophobicity of the backside of the material. The improved wettability of the material was attributed to the generation of oxygen-containing groups such as C–O and O–C=O on the plasma-treated TPU surface. Flor et al. [174] concluded that the ability of LTP treatment to give rise to unique textile products, which behave hydrophobic on one side and hydrophilic on the other side of the fabric, might open new avenues for smart clothing aimed at moisture and sweat transport management.

Anti-static finishing

The hydrophobic character of synthetic fabrics does not allow the formation of a conducting wet layer on the surface of the fibers. This results in accumulation of static charges that stay on the fabric for long periods of time, making the wearer uncomfortable. This static charge problem can be reduced by applying anti-static agents to the fabric. However, the traditional chemical-based anti-static agents have both technological and ecological problems such as, yellowing of fabrics, migration of anti-static agent from surface to bulk of the material, toxicity, and flammability. Plasma treatments are known to improve the hydrophilicity of textiles and may be an environmentally favorable alternative to conventional anti-static methods.

Kan and Yuen [175] investigated the effect of low-pressure RF plasma generated in oxygen under different conditions on the anti-static properties of PET fabric. SEM revealed significant morphological changes on the surface of the plasma-treated PET sample, which provided more capacity for PET to capture moisture and hence increase the dissipation of static charges. In addition, it was found that the increment of moisture content reduced the time for the dissipation of static charges. Moreover, it was shown that LTP treatment led to a greater improvement in the anti-static property of PET fabric compared to commercial anti-static finishing agent.

Samanta et al. [176] treated nylon and polyester fabrics with atmospheric-pressure glow discharge plasma using He and air. The anti-static properties of the samples were evaluated by measuring the static charge build-up and half charge decay time. Their results showed that 60 s air-plasma-treated nylon fabric produced only 1.53 kV of charge and showed a significantly smaller half decay time of 0.63 s compared to static voltage of 2.76 kV and a half decay time of 8.9 s in the untreated nylon fabric. In comparison, the He plasma-treated nylon fabric showed relatively less improvement by producing charge build-up of 2.12 kV and half charge decay time of 1.1 s. Similar improvements were obtained for PET fabrics. In addition, it was found that the treated samples showed good anti-static properties even after five laundry wash cycles. The improvement in anti-static properties was attributed to increase in surface energy due to the formation of hydrophilic groups and increase in the surface area due to the formation of nano-sized horizontal and vertical channels on the fiber surface. The authors concluded that plasma treatment may be used for imparting effective anti-static finish on hydrophobic substrates without the use of any anti-static chemicals.

Influencing mechanical properties of fiber

Plasma treatments usually do not negatively affect the mechanical properties of textiles. In fact, in some cases, there is an improvement. For example, Kan et al. [154] treated wool fabric with oxygen LTP and found that the breaking strength was enhanced after the LTP treatment and that the tearing strengths of fabric in warp and weft directions fulfilled ASTM performance specification requirements (ASTM D3780-95 and ASTM D4155-95). In addition, it was found that plasma-treated fabric exhibited a higher tensile strength than the untreated fabric and good extensibility. These findings were attributed to the roughening effect (of plasma treatment) which created more contact points in the fibers (microscopically), resulting in an increased inter-yarn and inter-fiber frictional force. Hence, more forces were required in order to overcome the inter-yarn and inter-fiber friction before the occurrence of fabric breakage, resulting in a higher breaking load. The modified elongation of plasma-treated fabric was also attributed to the cleavage of the disulphide linkage present on the fiber surface. This cleavage could soften the wool scales, thus making the fibers more elastic. Similarly, El-katib et al. [177] showed that oxygen plasma treatment induced a slight enhancement in both tensile strength and elongation % at break of the wool/polyester blend fabrics. Radetic et al. [103] reported that RF low-pressure plasma and corona treatment could provide decolorization of indigo-dyed denim fabrics. Moreover, it was found that breaking strength in weft direction increased from 2.7 to 5.3 % after both corona and low-pressure plasma treatment. The breaking strength in the warp direction, however, was not significantly affected by corona treatment, except in the case of treatment under the most severe conditions (45 passages, 1000 W), where an increase in strength by 3.9 % was observed. On the contrary, low-pressure plasma-treated samples showed lower breaking strength in warp direction compared to untreated sample, which was particularly pronounced after treatment in air plasma (9.4 %). The decrease in break strength after air plasma treatment might be attributed to the partial surface damage of fibers, as revealed by SEM observations.

Rombaldoni et al. [178] showed that HMDSO plasma polymerization of wool fabric induced an increase in bending rigidity both in warp and in weft directions as well as a great enhancement in shear rigidity. This result was attributed to enhancement of inter-yarn friction at yarn crossover points in plasma-treated fabrics. Seki et al. [179] investigated the effect of low-frequency (LF) and RF oxygen plasma treatment of jute fiber on mechanical properties of jute fiber/polyester composites. It was found that both LF and RF oxygen plasmas improved the tensile and flexural strengths of jute fiber/polyester composites. The interlaminar shear strength increased from 11.5 MPa for the untreated jute fiber/polyester composite to 19.8 and 26.3 MPa for LF and RF oxygen plasma-treated jute fiber/polyester composite, respectively. The authors concluded that oxygen plasma treatment of jute fibers by using RF plasma system instead of using LF plasma system brings about greater improvement on the mechanical properties of jute fiber/polyester composites. Gibeop et al. [180] showed that plasma pre-treatment of jute fibers improved the mechanical properties of jute/poly(lactic acid) biodegradable composites. As above, it was found that tensile strength, Young's modulus, and flexural strength were increased by 28, 17, and 20 %, respectively, for plasma-polymerized jute fiber composites. The improvement in the mechanical properties was attributed to the heat and etching effect of the plasma treatment which makes the rough surface of the fiber, enabling good interlocking between fibers and matrix.

Influencing physical properties of fibers

Plasma treatments also have the potential to influence the physical properties of textile materials, such as weight loss, whiteness and yellowness index, air permeability, water-vapor permeability, pilling resistance, thermal properties and fabric hand properties, and this without the use of water or chemicals. For example, Inbakumar and Anukaliani [181] treated silk and wool fabrics with low-temperature glow discharge air plasma and found that the weight loss of the plasma-treated fabric increased with increasing exposure time. This result was attributed to the etching of a contaminant layer. It was also found that silk samples were more susceptible than wool fibers to plasma treatment showing greater weight loss. This finding indicated that weight loss highly depended on the polymer structure.

Yip et al. [182] studied the effect of LTP treatment, using various gases, namely oxygen, argon, tetrafluoromethane (CF_4), and 75 %/25 % nitrogen/hydrogen mixture, on weight loss of PA filaments and fabrics. They found that an oxygen plasma induced a much higher material weight loss compared to others gases. This finding was attributed to the higher ablation tendency of oxygen plasma to the polymeric materials. Also, it was found that argon plasma treatment was the second destructive one followed by nitrogen/hydrogen plasma. Conversely, CF_4 plasma induced a slight increase in fabric weight. To explain this result, the authors suggested that hydrogen gas was present in the plasma chamber and that polymerization really came into the competition, resulting in a slight increase in the weight of CF_4-treated samples.

El-Zeer and Salem [183] revealed that atmospheric-pressure air plasma treatment induced an improvement of the whiteness of wool/PA blend fabric as compared to untreated samples. This improvement was found to be discharge current and time exposure dependent. However, Szabo et al. [184] showed that air plasma treatment slightly decreased the whiteness and increased the yellowness of raw linen fabrics and brought about perceptible change in color of the samples. Also, it was shown that this effect remained stable after storage for a period of 1–14 days.

Rombaldoni et al. [178] highlighted that HMDSO plasma polymerization caused a general increase in fabric thickness that is not only related to the deposition of a thin polymeric film over the substrate, but also to the induced roughness of the wool fabric, and that the difference between treated and untreated was more and more evident with the increase of load (2, 20, and 100 gf/cm^2). The authors outlined that the thickening could be one of the reasons for the decrease of air permeability. In fact, it was found that, after plasma process, there was an overall lowering in air permeability of wool fabrics, independent of process conditions tested. This finding was explained by the fact that increased fabric thickness resulted in changes that act as a boundary to hinder the air flow through the fabric, thus resulting in a reduction in the air permeability of the fabric. Prakash et al. [185] investigated the effect of oxygen atmospheric-pressure plasma on air and water-vapor permeability properties of single jersey bamboo fabric. Their results showed that water-vapor permeability increased, although the air permeability decreased along with the plasma treatment. The reduction in the air permeability of the plasma-treated fabric was attributed to the plasma action effect on increasing in the fabric thickness and a change in fiber surface morphology, which would act as a boundary to hinder the air flow through the fabric. The improvement in the water-vapor permeability of the plasma-treated bamboo fabric was explained by the fact that the grooves formed on the surface might cause a reduction in the capillarity pressure, which probably caused higher water-vapor permeability. Thus, a feeling of better comfort could be provided by increased water-vapor transfer with the help of plasma treatment. Similar results, using PA and PP fabrics treated with air, nitrogen and argon atmospheric plasma, were reported by Yaman et al. [186, 187]. They also measured the thermal resistance and thermal conductivity of treated PA woven fabrics and observed an increase in thermal resistance (approximately 43 %) and a decrease in thermal conductivity (approximately 8 %) [187]. These changes were attributed to the plasma etching effect increasing the fabric void degree, and thus the amount of air trapped between the yarns and fibers. The authors concluded that the physical properties of PA fabrics could be improved by using plasma treatments.

Karahan et al. [102] reported that air and argon atmospheric-pressure plasma treatments considerably improved the pilling resistance of cotton fabrics. This result was attributed to the reduction in the hairiness of the fabric. The authors assumed that the etching action of the atmospheric plasma treatment weakened the structure of the anchor fibers, therefore they became more fragile. As a result of these alterations, the abrasion resistance decreased. Ferri et al. [188] investigated the influence of atmospheric-pressure plasma treatment on the hand characteristics of wool fabric. Obtained results revealed that the treated fabrics were slightly softer and warmer than untreated ones. This finding was attributed to the increase of surface thickness and the decrease of thermal absorptivity after plasma treatment. However, Rombaldoni et al. [189] found that oxygen plasma-treated wool fabric dyed at temperature below the boil (85 °C) was stiffer and crisper than the untreated fabrics and untreated fabrics conventionally dyed at 98 °C. Thus, it could be stated that a gentle treatment is required for wool, since a strong plasma action might worsen the fabric handle, which is a critical physical property for consumers when making purchasing decisions.

Contribution of LTP treatment towards sustainable development

As has been illustrated, LTP technology offers an efficient alternative route for surface modification of both natural and synthetic polymeric materials providing the same or even better treatment effects. Further, plasma treatment can be used for the production of innovative textile materials with properties that cannot be achieved via traditional wet chemistry finishing. And above all these, LTP technology has a great potential to limit the environmental impact of textile processing and contribute towards sustainable development [190]. The environmental benefits from the application of plasma technology in finishing treatment are the followings [3]:

- Reduction of the amount of water used,
- Reduction of the amount of chemical needed in conventional processing,
- Better exhaustion of chemicals from the bath,
- Significant reduction of the chemical and biological oxygen demands (COD and BOD) of effluents,
- Shortening of the wet processing time,
- Decrease in needed wet processing temperature, and
- Energy saving, due to the elimination of the need for drying or curing.

In fact, plasma treatment is a dry physical process that requires only a gas as the medium for interacting with the textile materials, thereby eliminating the need for water and solvents in modifying important surface properties. In many cases, the desired functionalities are obtained just by using air, oxygen, nitrogen, or other “inert” gases which are usually non-toxic, i.e., environment friendly. It does not produce any waste/load on the environment, and thus reduces additional costs related to the storage and disposal of chemicals. This lack of harmful by-products is a major advantage of plasma surface treatments over wet-chemical methods. The other main advantage is that the textile material integrity is maintained while there is a large possibility of fiber degradation during chemical treatment. Furthermore, plasma processing is rapid, extremely versatile and is carried out at room temperature, thus limiting the amount of energy necessary for heating water, drying, and curing [190]. It, therefore, has the potential to meet all the goals of a modern sustainable production process.

As mentioned above, plasma treatments can replace traditional wet-chemical-based processing to reduce direct costs and environmental impact. For example, atmospheric plasma finishing can be a viable replacement for conventional pad-dry-cure process, which requires high levels of thermal energy to evaporate water and cure the fluoropolymer. In fact, atmospheric plasma processing can impart a repellent finish on a textile and does not require high levels of thermal energy because there is no water to evaporate and the fluoropolymer polymerizes in the plasma; therefore, it does not need to be cured. In this way, an LCA study [191] about imparting oleophobic properties on a PET substrate showed that energy requirements were three times greater for traditional process than for plasma process. It was also shown that the environmental impact of innovative plasma processes contributes considerably less (at least a factor of two) to global warming (CO_2 emission), photochemical ozone formation, and to the acidification, and the eutrophication of local water systems. In addition, atmospheric plasma-applied repellent finishes can involve different hydrophobic reactants that have not been shown to be environmentally hazardous. Hauser et al. [192] highlighted that polymerizing fluorine-containing acrylic monomers on cotton fiber surfaces with atmospheric glow discharge plasma imparts a repellent finish comparable to the conventional pad-dry-cure repellent finish. Pane et al. [193] reported that plasma treatment can replace traditional method of finishing (washing and coating) for waterproofing of acrylic fibers for outdoor applications. Zhang et al. [194] showed that the water-repellent properties of plasma-coated cotton fabric were superior to those of Scotchgard-sprayed samples within short treatment time (30 s). Davis et al. [195] showed that atmospheric-pressure plasma could be successfully used to confer durable water-repellent functionality on cotton/polyester blend fabric. Nevertheless, it should be underlined that durability is highly process dependant and many atmospheric plasma processes does not deliver the same level of durability to laundering, as wet coatings. However, atmospheric plasma coatings are rapidly improving in performance to become competitive with wet coatings [5].

The replacement of the traditional stonewashing processes with plasma treatments also shows promise. Ghorannevis et al. [196] reported that low-temperature argon plasma treatments could replace less eco-friendly conventional stonewashing or enzymatic bio-stoning processes, which are used to create the popular “worn look” of indigo-dyed denim fabric. Indeed, plasma treatment can produce various shades of denim, without any impairment of the mechanical properties of the treated material. Therefore, the implementation of plasma technology in denim finishing might solve the problems of dust and effluent production as well as eliminate the use of water and chemicals, and reduce overall energy usage.

Substituting a plasma treatment for the chlorination process seems to be very attractive because this technique causes less degradation of the wool fibers and avoids the presence of absorbable organic halogens (AOX) in the waste water. Also, it gives advantages regarding operator health and safety since no hazardous chemical ... and the risk of industrial accidents is lowered. Hesse et al. [197] reported that glow discharge treatment of wool in non-polymerizing gases like air, oxygen, and nitrogen represents a new zero-AOX pre-treatment for shrink-proofing wool top and fabric, which could be an effective substitute for the conventional anti-felt treatment. Kan and Yuen [198] highlighted that atmospheric nitrogen plasma treatment alone could achieve the best anti-felting effect of wool substrates. It was found that hand feel was adversely affected by plasma treatment, but this property was favorably restored on polymer application [199]. Therefore, it can be concluded that plasma treatment is compatible with the trend of textile processing towards a zero discharge of harmful chemicals to the environment.

Plasma treatments cannot replace all traditional wet-chemical processes in the textile industry, such as dyeing and some finishing. Nevertheless, it is still capable of contributing towards environment protection. Indeed, if used as a pre-treatment, plasma treatment can markedly improve the water absorption of fabrics, thereby reducing the amount of chemical substances needed in conventional processing with better exhaustion of chemicals from the bath [3]. Moreover, shortening of the wet processing time and decreasing the required wet processing temperature may save limited energy resources [3]. Sun and Sytlios [139] highlighted that LTP oxygen pre-treatment improved scouring and dyeing processing of wool and cotton fabrics by nearly 50 %. This result indicated that a shorter time might be chosen for scouring and dyeing, which can lead to energy saving. Souto et al. [200] showed that DBD plasma pre-treatment highly improved the dyeing rate, dyebath exhaustion, and dyeing uniformity of PA fabrics, resulting in lower processing time, dyeing temperature, and dye concentration, which is an excellent opportunity to reduce costs in energy, dyes, and chemicals, achieving sustainable solutions ready for industrial application. Radetic et al. [3] reported that low-pressure RF plasma led to a remarkable increase in dyeing rate and final dye exhaustion of knitted wool fabrics compared with conventionally chlorinated sample. The higher dyeing rate indicates the possibility of shortening the dyeing time and the reduction in energy consumption since less time is needed to obtain the desirable state of dyeing. The higher dye exhaustion pointed out that the plasma-treated materials may require less amounts of dyestuff for a desired shade, which in turn can possibly contribute to a diminished effluent load. In another study, Radetic et al. [14] outlined that the color yield of plasma-treated printed wool samples did not reach the efficiency of a conventionally chlorinated sample; however, short plasma treatments did provide adequate preparation of wool knitted fabric prior to printing. This is very important from environmental point of view since conventional preparation of wool for dyeing and printing is carried out by chlorination process. Rakowski et al. [201] reported that plasma treatment could not only reduce chemicals and water consumption, but also save energy consumption by 90 % compared to conventional printing process on wool fabrics.

Plasma technology can play a pivotal role in adhesion processes. Plasma pre-treatments can increase the adhesion between the textile and the coated layer, and in many cases, lead to a more uniform coating layer being applied. Thus, a pre-process, such as the application of a chemical primer or a solvent process, can be avoided. They can also reduce the amount of coating substance required, and likewise the amount of waste. Gibeop et al. [180] highlighted that plasma pre-treatment greatly enhanced the adhesion properties of jute fiber/poly(lactic acid) composite compared to alkali (NaOH) treatment. Thus, it can be concluded that plasma treatments are an effective and eco-friendly alternative to traditional wet-chemical methods.

Besides, plasma technology is a promising pre-treatment to improve desizing efficiency and reduce processing time or cycles. Li et al. [138] showed that He/O_2 atmospheric plasma treatment could significantly reduced desizing time and improved blended size removal compared to conventional wet desizing process. In addition, it was found that the desizing temperature was also considerably reduced (to 60 °C) by combining plasma treatment with ultrasound treatments [202]. The authors concluded that the combination of APPJ and ultrasound showed higher effectiveness in desizing and provided an alternative approach that decreases the water, energy, and chemical consumption. Bulut et al. [203] observed that the desizing degree of both PVA and starch ether sized cotton fabrics was high after a 20-min atmospheric plasma application, even though no washing was done after the plasma process. The authors highlighted that the operation cost could be reduced by at least 90 % if desizing and gassing are connected with plasma treatment, skipping at least two washings and desizing steps in the process, which is significant in terms of cost, workload, and especially ecology. Thus, it can be drawn that plasma-aided desizing is a highly efficient treatment that can save energy and water resources.

In summary, plasma treatment is a rapid and one-step process that can eventually enhance productivity and eliminate many of the environmental problems associated with the textile industry, especially those related to water pollution. It is expected that this innovative and environment-friendly technology will lead to substantial savings in water, chemicals, and energy, and therefore, save production costs and increase profitability. Fast through-puts are potentially possible which would lead to an even further reduction in unit cost. Vertical processing is also possible which would minimize equipment foot-print and optimize valuable floor space. Moreover, this process can be used to improve the quality, performance, and useful life of the final textile products, and has the potential for innovation and development of new products. These factors, together with its flexibility and inherent safety, open the way to new business opportunities. Consequently, it can be concluded that plasma technology will contribute to satisfying future needs in term of resources and environment-friendly sustainable processes and products.

Hurdles of LTP treatment in the textile industry

In spite of the tremendous advantages of plasma treatment and of the wide range of applications possibilities, this technology is still in the stage where only first adopters are acting. In fact, its industrial application in textiles is still very limited. This cannot be attributed to one single factor. Rather, it seems to be due to a mixture of limitations that stems from (i) the plasma technology itself, (ii) textile sector-related issues, and (iii) specific textiles properties.

Plasma technology related causes

Possible reasons linked to the plasma technology include the following:

Reproducibility of the process

Plasma process parameters are highly system-dependent. In fact, the optimal parameters developed for one system are not necessarily valid and equally applicable for another system. Furthermore, the scale-up of an experimental setup to a large production reactor is not a simple process. In other way, there are many process parameters (such as power level, gas flow rate, gas composition, gas pressure, sample temperature, reactor geometry, electrical input, and time of exposure) to control, making plasma process extremely complex. Also, in most cases, it is impossible to calculate the physical and chemical behavior of a plasma due to the huge amount of elementary reactions that occur, and thereby, it is very difficult to control precisely the amount of a particular functional group formed on a surface. Therefore, a thorough knowledge of plasma surface interactions is of prime importance in order to better understand, control, and optimize the plasma process. Moreover, designed plasma processing systems should be simple and relatively straight forward.

The stability during long-term industrial operation

Plasma-treated surfaces age at different rates and to varying extents relative to factors with the surrounding environment such as temperature and humidity, leading to gradual loss in the imparted properties. This instability of modified surfaces limits their use in many practical applications and thus, hinders commercializing the plasma process. In fact, the wider applications of plasma-treated polymers depend on their long-term properties. For this reason, it is important that the change in surface chemistry with time is more fully understood, particularly in applications where specific surface functionalities are required. In this way, it is recommended to bond, coat, dye, or paint the modified surface as soon as possible following plasma pre-treatment so that the high surface energy that is obtained as a result of plasma treatment can be technically useful.

Operating speed

Line speeds need to be as fast as or faster than existing technologies to avoid bottlenecks and reduce unit production costs. Whether or not this is an issue is entirely process dependent [5]. In some cases, atmospheric-pressure plasma treatments run slower than target line speed, which is a serious obstacle that would limit commercializing the in-line atmospheric-pressure plasma systems on a large industrial scale. Thus, a need exists for technically and economically feasible plasma sources that are capable to provide the high throughput needed for continuous processing of large area materials. In this way, DCSBD plasma sources working at atmospheric-pressure in open air can address the needs of textile industry [204]. In comparison with other atmospheric-pressure plasma sources, DCSBD offers outstanding performance with extremely low energy consumption for large area, uniform surface modification of materials under continuous process conditions [204, 205]. This technology was successfully tested for the in-line activation of PP nonwovens at the line speeds up to 300 m/min with an extremely low energy consumption less than 0.3 kWh/kg [204]. Also, it was confirmed that atmospheric-pressure DCSBD could improve the surface properties of reinforcing PP fibers [206, 207]. In addition, DCSBD plasma was used for imparting anti-felting properties to animal fibers [208, 209]. Thus, the application of DCSBD plasma treatment in the textile industry can be inexpensive, high-speed, and accomplished in-line. In another hand, the inductive coupled plasma is a promising low-pressure, high density plasma source for material processing that can cope with the typical speeds needed for industrial operations. It also provides improved plasma uniformity over wide area with low cost of operation [210, 211]. Hence, this technology is of great importance to modern plasma technology.

Textile sector-related issues

The textile sector-related causes, which hamper the integration of plasma into the production process, can be identified as follows:

Existing equipment

Nowadays, the textile industry manages the required coating and finishing steps with existing equipment which often consists of simple mechanical methods. Substitution of that equipment with much more expensive plasma technique is always difficult and has much longer pay-off times, especially if water, energy, and waste treatments costs are not exactly taken into account. The availability of machinery is still limited and those on the market are not flexible enough to obtain good results in a relatively large range of possible applications. This can be attributed to the slow development of suitable industrial systems and the late focus on developing in-line atmospheric plasma systems. Therefore, a strong effort should be made by machinery manufacturing companies in order to really push this technology. Furthermore, environmental organizations should raise public awareness about the practical applications of plasma technology for environmental protection.

Sector organization

Due to the special industry nature, small- and medium-sized textile enterprise capital strength limits their capacity of investing in more expensive equipment. In fact, the most formidable problem faced by this kind of enterprise has been in accessing in technology and maintaining competiveness in the international market. This can be attributed to their poor financial situations, desire to avoid risk, nonavailability of technically trained human resources, and isolation from technology hubs. Therefore, in order to enable small- and medium-scale textile enterprises to overcome the problems of technological backwardness and enhance their access to new technology, it is imperative to offer them a conducive environment which includes building up technological capacity, knowledge flows, and technology databases.

General market conditions

The commercial application of plasma technology in the textile industry has not gathered momentum because of the lack of public transparency regarding the successes and failures of industrial trials. Moreover, as market conditions change towards industrial demand, the textile industry is considerably affected by increased international competition. This seems to lead to some combination of technological and market dualisms. In fact, such an environment does not really favor decisions to start more risky investment plans. Indeed, the textile manufacturer will not want to introduce a newly plasma process as it could potentially create a bottleneck in an existing line and become a rate-limiting step in a drive to increase line speeds. Thus, the integration of plasma technology in the complex textile productive chain is too difficult at the current time and will take place on a large scale only when the technology has clearly proven its advantages with respect to traditional wet processing methods.

Specific textiles properties

The main textile material-related issues that still hamper practical implementation of plasma processes in the textile industry are the chemical composition, the surface cleanliness, the three-dimensional structure, and the large surface area.

Chemical composition

The textile fabrics and yarns are often made from of a blend of fibers, like for example nylon and cotton that need to be treated simultaneously. In this case, the effect of the plasma treatment on the different materials will not be identical, and thereby, this will complicate the process to be optimized. In fact, the optimum conditions for plasma surface functionalization deviated for each textile material. Therefore, good knowledge of the substrate was essential for the manipulation of the plasma processing of different textile materials.

Surface cleanliness

Fiber surface cleanliness is an important issue today in the textile industry since it greatly affects both the efficiency and quality of plasma treatment. In fact, contaminations of the surfaces such as dust, dirt, and grease inhibit adhesion and can cause erroneous test results because plasma only interacts with these contaminations instead of the surface to be treated. Therefore, substrates must have been clean surfaces in order to achieve optimal pre-treatment and subsequent adhesion. This implies introducing new cleaning steps in the textile process before carrying out plasma treatment.

Three-dimensional structure of textiles

Textile materials can be very porous, and therefore, plasma can penetrate deeper into such a porous structure which will enable the treatment of surfaces of individual fibers also inside the textile web. Hence, the penetration of the plasma effect into the three-dimensional porous structure of textiles would determine the quality of the plasma treatment. However, the degree of plasma species penetration is closely linked to the textile structure. In fact, for textiles with a low porosity, the penetration of plasma active species is difficult which would lead to lower treatment efficiency throughout the fibrous structure. Therefore, more energy is needed to treat the surface of all single fibers within the entire fabric in order to obtain sufficient surface oxidation. This effect can be attained by reducing fabric speed or increasing discharge power. Nevertheless, the plasma treatment should be run as short as possible not only for economic reasons, but also because long plasma treatments can damage the fibrous substrate, which can have a detrimental effect on the mechanical properties of a fabric.

Large surface area

Textile materials differ from other materials mainly by their complex structure showing opening at different length scale (micro- to nanometer range) such as filament or interfiber distances. Because of this, the surface area to be treated is much larger for a textile substrate than for a flat film [32]. Moreover, because of the limited penetration of plasma-created species, the effectively treated surface area is substantially lower than the total available surface area. In order to generate a surface density of functional groups comparable to foils, it is necessary to generate considerably more reactive sites. Therefore, textiles must be exposed to a plasma for longer periods of time, in order to compensate the disadvantage of large surface area. Hence, plasma treatment time and electrical power have to be set up depending on both the material structure and the effect needed in order to ensure optimal treatment.

Positive examples

Despite the difficulties and obstacles described above, nowadays, some textile companies have already adopted plasma technologies and the interest in plasma is growing. An example of these companies is the Austrian textile finisher Texilveredelungs GmbH Grabher, which has developed an environmentally friendly process for imparting hydrophilic and hydrophobic functionalities to textiles [212]. Also, the Avondale Mills (Georgia, USA) is one of the first textile companies that make use of plasma technology for treating cotton and cotton/polyester fabric to provide stain and water repellency [213]. The Canadian Richter International company has put into the market the product called "Plasmawool" which is the first ecologically friendly collection of superfine merino wool stocks using water and chlorine free manufacturing [214]. The Pavlovo Posad Shawl Manufactory (Moscow region, Russia) has successfully introduced plasma treatment of fabrics before printing instead of using ecologically harmful chlorination process to make woolen fabrics non-felting and non-shrinking [215]. In India, the Angora cottage industry at Kullu has successfully used atmospheric plasma technique for spinning of 100 % Angora yarn and making newer products [216]. Following the successful use of plasma-based technology by first adopters in the textile industry, many plasma technology suppliers have made considerable efforts to develop both low-pressure and atmospheric-pressure-based plasma machinery and processes designed for industrial treatment of textiles to meet customer demands and offer tools for product development and innovation. The standard and custom-designed plasma (treatment) systems being offered in the market are (i) Low-pressure plasma systems for in-line and batch treatment by Europlasma (Belgium), P2i (UK), Mascioni (Italy), and HTP Unitex (Italy). (ii) Atmospheric-pressure plasma system for on-line continuous treatment by Dow Corning Plasma Solutions (Ireland), Ahlbrandt (Germany), AcXys (France), APJeT (USA), Tri-Star (USA), Softal (Germany), and Arioli (Italy) [32, 217]. Moreover, further technology development is in full progress. Therefore, it is possible to envisage that, in the near future, plasma technologies will become commonplace in the textile industry.

Conclusion

Low-temperature plasma technology potentially offers a versatile, flexible, clean, and eco-friendly finishing approach for imparting much desired functional properties to textile substrates to meet specific requirements, with lower environmental impact. Indeed, the discharge of harmful chemicals can be eliminated with the use of plasma treatment, which can thus be considered as a sustainable process that is competent to supersede the conventional chemical finishing of textile materials. Another advantage of plasma treatment is that the surface properties can be enhanced selectively in relatively short processing times without impairment of the original bulk properties of the treated material. Further, plasma treatment can be used to create innovative surface characteristics that are beyond the reach of traditional wet chemistry finishing. Thus, plasma technology can make important contribution to sustainable growth, innovation, and new products. This tremendous potential explains why plasma treatment has already been investigated extensively in laboratory scale. In contrast to this, the industrial use of plasma-based processes in the textile industry is still modest. This is because important hurdles exist at various levels: with the plasma technology itself, with the textile sector-related issues, and because of bottlenecks due to the specific properties of textile materials. Therefore, the implementation of plasma technology into the textile industry requires a careful consideration of the fabric properties such as fabric structure, composition and fiber surface purity, as well as an appropriate choice of plasma processing conditions in order to ensure optimal treatment results. Indeed, a clear understanding of plasma surface modification process is necessary to improve the commercial viability of this technology and offer tools for product development and innovation. Meanwhile, plasma processing with all its challenges and opportunities is an unavoidable part of our future. Therefore, both the technology developers and the textile industry need to work closely together and have the courage and foresight to implement a long-term strategy of sustained investment in plasma technology. Nevertheless, today, plasma technology is already being integrated within the textile industry by first adopters for niche applications and, taking into account the growing environmental and energy saving concerns, it can be predicted that the adoption of this innovative technology will expanded into high volume markets.

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