A New Dielectro-phoretic Coating Process for Depositing Thin and Uniform Coatings on Films and FibrousSurfaces

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ABSTRACT

The deposition of very thin functional coatings on polymer films and fibrous substrates is a challenge when using low percent solids in aqueous or solvent based solutions and practically impossible when using 100% solids. The challenge becomes even greater when coating fibrous materials such as paper, foam, and woven and non woven membranes and textiles with viscous solutions. Sigma has developed a proprietary coating technology that allows surfaces to be uniformly coated with relatively viscous monomers and water and solvent based solutions where the water and solvent are minimized to save energy and minimize coating costs. The coating process is composed of three separate and independent steps. An atmospheric plasma treatment station is used to improve surface energy, a coating module in then used to apply the coating and aDielectrophoreticstation is used to spread the coating on the surface using an electro-hydrodynamic force. The latter system acts upon the liquid with a force that can be controlled by the application of an electromagnetic field on the coated surface.This process is so effective, that a viscous liquid deposited on one surface of a non woven material can be driven to coat the fibers within the bulk of the fabric structure, as well as the opposite surface. The coating module consists of a series of ultrasonic spray nozzles. The coating system is particularly effective when coating fibrous surfaces with viscous solutions, or 100% solids in conjunction with radiation curing. Ultrasonic based coatings can also be effective in reducing the amount of solvent and water required in conventional coating formulations. The micro-droplet formation leads to water/solvent evaporation during the coating step, which reduces drying time. For many applications conventional coating equipment may be used and the treatment and dielectro-phoretic stations may be retrofitted into existing coating lines

to improve the layer uniformity of thin coatings and facilitate penetration into fibrous surfaces.

THE DIELECTROPHORETIC COATING PROCESS

The process is shown schematically in Figure 1. A web substrate is first plasma treated to enhance surface energy and form covalent bonding groups with the liquid monomer. The liquid monomer is then applied using an ultrasonic atomization process that forms monomer micro-droplets, which are guided onto the substrate surface with the assistance of a controlled air flow.

The plasma treatment and coating process using ultrasonic atomization can be used for any type of substrate and the coating formulation may be water/solventbased or 100% solids cured by UV or electron beam. The coating thickness is typically less than one micron and can be very uniform and glossy. Although the ultrasonic atomization offers some advantages, other conventional coating methods can be equally effective in coating various substrates (films, foils, etc) that have a relatively smooth surface.

The process described here is particularly effective for functionalizing substrates that have some surface microroughness and/or porosity, such as non woven and woven textiles, foams, membranes, paper, fabrics, composites, etc. That is, a very thin coating is required to alter the material surface (and functionality) with no significant effect in the intrinsic properties of the porous material, such as hand, feel, breathability, tensile strength, etc.. Such surface functionalization is virtually impossible to do when using radiation curable monomers (100% solids) in conjunction with conventional coating techniques, as such techniques have the effect of clogging pores and openingsin the media structure. In fact, this is not possible even with a non-contact process like ultrasonic atomization, assisted by plasma treatment. Although theplasma treatment process helps the droplets wet the fiber surface, after some experimentation it was established that if the size and number of droplets per unit area is low(in order to produce a thin coating),many small droplets that land on fibers do not wet the surface. This effect is magnified when the droplet diameter and the fiber size or surface micro-roughness is of the order of few microns. The high surface tension of a small monomer droplet as well as the suspension of the droplet between fibers results in an effect similar to the super hydrophobic effect of a lotus leaf.That is, the droplet has a wetting angle greater than 150^o, even if the surface of the fibers has high surface energy.This results in poor quality coatings, which alter the “feel” or “hand” of a fibrous substrate. In extreme cases the surface of a soft fabric can feel as coarse as sand paper after UV cure.

When applying a high amplitude electrostatic or electromagnetic field in the immediate vicinity of the deposited coating, inline with the coating process, any droplets that may be present will be moved rapidly in random directions and breakdown to form a thin liquid layer. Thicker liquid layers will also move, resulting in a uniform coating with high penetration into the substrate volume. Given an adequate quantity of liquid the coating can move from one surface of a micro-porous substrate to the opposite surface, thus fully coating the volume between the two surfaces with a nano-thick monomercoating.

The movement of the liquid is due to a dielectrophoretic force that is generated by the applied field due to the difference in dielectric constants between the substrate, the monomer coating and the surrounding air. When exposed to an electric field, the higher dielectric constant liquid monomer material will move away from a field non-uniformity in the direction of the lower dielectric constant medium. A liquid layer on the surface of a fiber that is immersed in an electric (or electromagnetic) field will be forced to move in a direction perpendicular to the applied field away from the fiber and into the air space (which has the lowest dielectric constant).When the surface tension force that exists between the liquid and the fiber is superimposed, as well as the random fiber orientation, the liquid instead of jumping off the fiber surface, moves along the surface with a force that is proportional to the applied field, the dielectric constant of the liquid, and to a lesser degree the dielectric constant of the fibrous medium. Thin liquid layers that are already well distributed in the fiber matrix will move relatively little, while thicker layers or droplets will disperse into thinner layers and move deep into the volume.

Unlike conventional wet processes, the dielectro-phoretic coating process is designed specifically for the deposition of nano-engineered,radiation cured,functional layers using an environmentally friendly, energy efficient process that has a low carbon footprint. The dielectrophoretic coating process possesses a number of supplementary advantages over conventional treatment processes, some of which are listed below.

- Coating process has all the advantages of conventional 100% solid radiation curable coatings
- Does not alter mechanical properties and feel of porous substrates
- Can be used to treat one or both sides of a porous substrate with same or different functionalities. This is not possible with conventional “wet” coating processes
- Can utilize functional monomers mixed with nanoparticles (eg SiO_2, Al_2O_3, TiO_2).
- Plasma treatment promotes bonding of the coating to virtually any substrate
- Lower material costs
- Zero emission of Volatile Organic Compounds (VOCs) and Hazardous Air Pollutants (HAPs)
- Energy consumption and occupied space is a small fraction of wet processes
- Broad Range of Monomer Chemistries:

- Free Radical PolymerizableAcrylates
- CationicallyPolymerizable Materials
  - Epoxies
  - Vinyl monomers
- Clear and Transparent Films
- Anti-Stain
- Anti-flammable
- Anti-bacterial
- Chemical Sensing - Color Change
- Color
- Heat Sealing
- Ionically Conductive
- Electrically Dissipating
- Release

EQUIPMENT DESCRIPTION

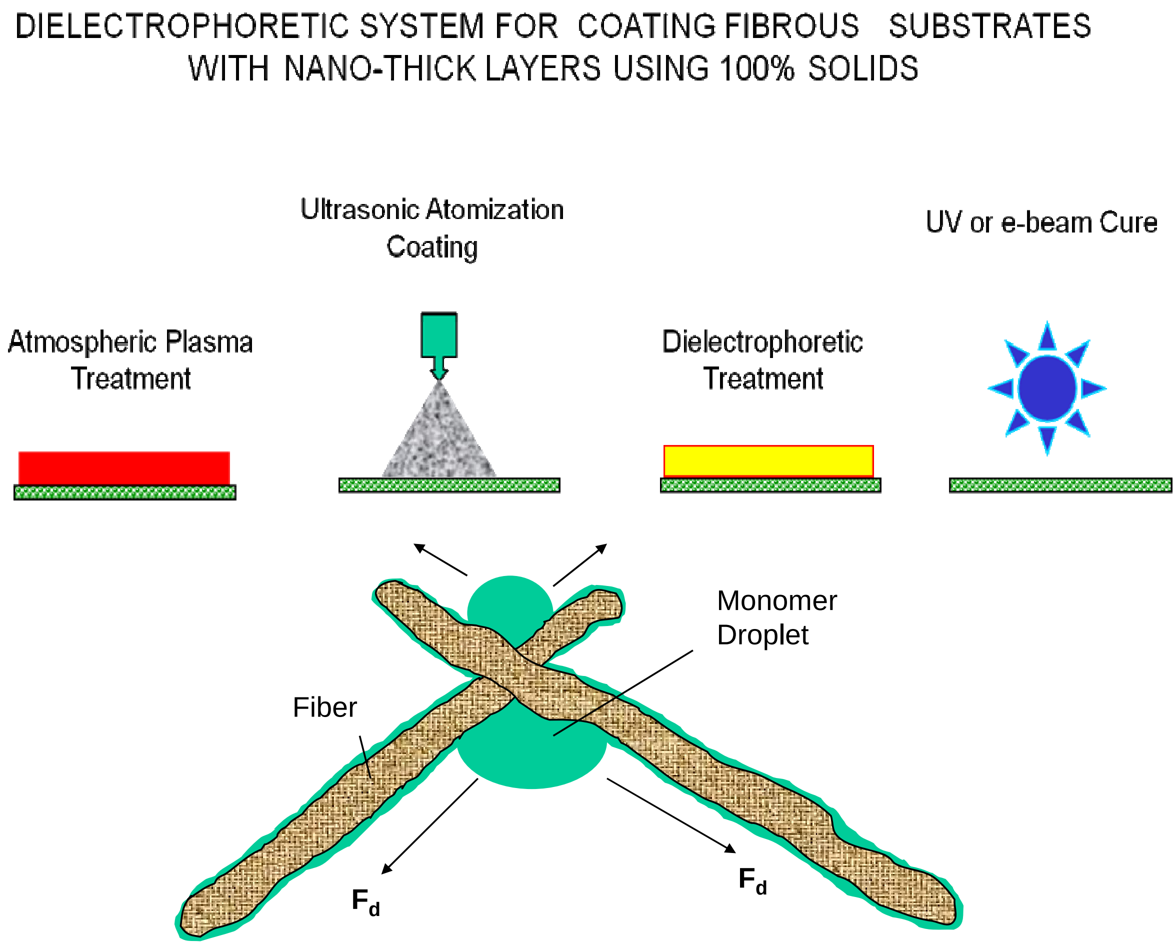
Plasma Treatment Station

Sigma has pioneered large scale plasma treaters for web applications. Sigma 's Atmospheric Plasma Treatment (APT) system is designed to provide superior quality surface treatment to various substrates, including polymer films, woven and non woven textiles, membranes, paper, sheet metal, powders etc. For this application the plasma system is designed to prevent pin-hole formation on the porous substrates, which will occur if corona is used for treatment. The APT system is poweredby a mid frequency generator, and it is integrated with PLC controlled gas mass flow systems that control the plasma gas through the electrodes. One or more plasma gasses can be fed into the treater chosen from a variety of gases that include, N, Ar., He, O_2, C_2H_2 and others. The properties of treated substrates include:

- Uniform surface treatment
- High surface energy (>50dynes/cm)
- Increased wetability and bonding
- Higher and longer-lasting treatment levels

Ultrasonic Atomization – Monomer Deposition Station

A linear array of ultrasonic atomization nozzles are used to deposit the monomer coating on the moving web. The number of nozzles may vary depending on the application. A precision metering pump is used to feed the liquid monomer into the nozzles. The micro-droplets produced by the ultrasonic nozzles are guided and forced onto the surface with an integrated airflow system.



Dielectro-Phoretic Force F_dForces Excess Liquid To Move
Randomly on Fiber Surface

$$F_d \propto \frac{1}{2} \kappa \ \ V \ \ \nabla E$$

Where: $\kappa$is the dielectric constant of the monomer liquid, κ is the volume
and ∇**E** is the Field Gradient

Figure 1. Top: Schematic representation of a Dielectro-PhoreticCoating process for coating porous substrates using radiation curable 100% solids monomers. 4-Step process composed of atmospheric plasma treatment, monomer deposition using ultrasonic atomization, dielectro-phoretic station and UV or e-beam curing. Monomer formulations may include nano-particle functional additives. Below: The applied electromagnetic field generates a dielectro-phoreticforce F_d which breaks up monomer micro-droplets and forces the thicker layers of monomer (or nanoparticles) to propagate into the volume of a porous substrate.

Dielectrophoretic Station

The dielectrophoretic force can be generated both with DC or AC voltages. In order to effectively drive the liquid into the volume of a porous material, a very high field is required, which is often difficult to apply without occasional partial discharges which can damage the substrate. This is avoided by using a plasma stationthat is virtually identical to the plasma station. The substrate fibers are immersed in the plasma which conducts the field into the immediate vicinity of the liquid and maximizes the driving force. Unlike the plasma treatment station whichmay utilize reactive gases to enhance the surface energy of the substrate, the plasma in the dielectro-phoreticstation utilizes an inert plasma gas such as nitrogen mixed with argon or helium. Reactive gases may also be used if in addition to moving the liquid layers it is desirable to impart additional functionality onto the liquid surface. The intensity of dielectrophoreticplasma station is adjusted based on liquid movement rather than treatment level. Depending on the type ofsubstrate and applied field, the coating can be limited to one side of the substrate or it can be driven through the material onto the back substrate surface,

UV or Electron Beam Curing Station

Typically a high intensity,medium pressure, mercury arc lamp is used to cure the deposited coating. The lamp system incorporates a pneumatically driven shutter,which minimizes substrate heating. Given the low coating thickness, a relatively low level of radiation is required to cure the coatings.

SUMMARY

The plasma assisted ultrasonic-dielectrophoretic coating process has resulted in the deposition of nanothick functional polymer coatings on various porous substrates such as woven and non woven textiles and paper. The coatings can be made thin enough to functionalize the substrate with no significant effect on the “feel”, “hand” or porosity and breathability of the coated material. The process is environmentally friendly and cost competitive with water/solvent based processes. Coating formulations are virtually the same as those used in various protective coatings that utilize radiation cured chemistries and can include nanoparticle additives. Unlike “wet” coating methods,nanothickdielectrophoretic coatings can be deposited only on one side of a porous substrates, resulting in materials that have a different functionality on each substrate surface.