

BREATHABLE WATER-RESISTANT LINERBOARD COATINGS BY ELECTROSPRAYING APPLICATION

Erica Ford,^a Roman E. Popil,^{b*} and Satish Kumar^a

Waterproofing of corrugated packaging with wax or polyethylene hinders recyclability and so is incompatible with current socioeconomic goals of sustainability. Therefore, alternative coating technologies are sought. This study describes our feasibility study of electrohydrodynamic spraying (EHS) towards waterproofing corrugated boxes. Water resistance properties of electro-sprayed polymer-solvent solutions and latex systems air dried onto linerboard surface are reported. Optimization of spraying parameters led to observations of applied coating roughening on a nano-to-micron scale that correlated with increased water contact angle of the treated linerboard. An EHS latex formulation, compared to polymer solvent system, has shown better adhesion to linerboard. EHS application of latex produced a surface coating texture of droplets, which minimizes liquid water absorption, forming a nanopore matrix (of 3 – 50 nm diameter pores) that enabled the transmission of water vapor. Linerboard treated by EHS latex was advantageously found to be comparatively transpiring to water vapor at room temperature and refrigeration conditions, which is encouraging for commercial application of the technique.

Keywords: Coating; Linerboard; Electrohydrodynamic spraying; Polymer; Water resistance

Contact information: a: School of Polymer and Textile Technology, Georgia Institute of Technology, Atlanta, Georgia 30332, b: Institute of Paper Science and Technology, Georgia Institute of Technology, Atlanta Georgia 30332, USA; Corresponding author: roman.popil@ipst.gatech.edu

INTRODUCTION

This report is part a research program concerning various means of waterproofing paper corrugated packaging (Popil 2006; Popil and Joyce 2008; Popil and Schaepe 2005). The goal of this particular investigation was to specify a nanotechnology-based coating for corrugated containers that has socioeconomic competitiveness with traditional coating processes and plastic containers. The attractiveness of nanotechnology centers on the potential to achieve hydrophobicity at lower coat weight and reduce the energy required for surface heating drying or curing an applied coating, while maintaining the recyclability of corrugated wood-derived fiber packaging. The traditional wax coating of curtain-coated boxes made with impregnated corrugating medium or cascaded with wax is derived from increasingly unavailable petroleum distillation by-products but offers water and moisture barrier properties that surpass other protective coatings intended for corrugated containers. Wax coatings performance characteristics serve best to maintain the structural integrity and strength of ice-filled containers under refrigeration conditions.

However, the inability to easily recycle these one-time-use packages is unattractive for retailers.

Re-usable plastic containers (RPCs) are a major threat to the corrugated industry's market (approximately 3.6 million tons (CPBIS 2008)) for nondurable food packaging. Recyclable corrugated containers offer economic competitiveness with RPCs, while increasing the tonnage of recyclable old corrugated container (OCC). The price of used OCC ranges between \$60 to \$200/ton (Backus 2007), which also works in the favor of retailers who resell the OCC for recycling. Case studies by Corrugated Packaging Association (CPA) have shown corrugated boxes to be more economically favorable than RPC's, especially when boxed non-durables are shipped under refrigeration conditions without ice.

The commercialization of latex coating for wax coating replacement satisfies the sustainability requirements of retailers for recyclable packaging. Latex coatings have been shown to impede liquid water absorption and water vapor transmission. However, the process of latex coating requires additional production costs of offline or on-line coating application followed by elevated temperature drying by air impingement, IR irradiation, or a combination of both. Latex coatings successfully reduce the coat weight for water resistance compared to wax by a factor of 5; however the raw material costs of latex is approximately 5 times greater than wax per pound. Clay has been investigated as a micron-sized filler that is capable of reducing the water absorption and coat weight of the more expensive latex (Andersson *et al.* 2002; Popil 2006; Popil and Joyce 2008; Popil and Schaepe 2005). Talc filler, which is slightly more costly than clay, has also been investigated within latex composites for waterproofing corrugated containers (Popil 2006; Popil and Joyce 2008; Popil and Schaepe 2005). Both clay and talc demonstrate a trend of employing particulates on the order of sub-to-microns length scale in the preparation of barrier coatings.

Gore-Tex[®] fabric is an archetype for a multilayered, barrier selective coating via microporous mats of hydrophobic fibers; this structure is water resistant but has high vapor transpiration through its matrix of pores. Electrospraying is considered here as a possible mechanism for producing a similar (sub)micron structure in order to waterproof corrugated paper packaging. Commercial application of electrostatic assisted spraying has been commonly utilized by crop dusting airplanes, as well as painting of automobiles and appliances. The applied voltage must overcome the surface tension of the polymer solution for the solution to become unstable, disintegrating upon exiting from an orifice into uniformly small electrostatically charged droplets or filaments (Ramakrishna *et al.* 2005). The aqueous and/or organic solvent of the coating formulation evaporates upon its being dispersed into a spray, while a formed polymeric-solid on the nano to micron scale traverses from a charged pipette orifice towards a grounded collection plate. **Fig. 1** is a schematic of typical lab-scale electro-hydrodynamic spraying (EHS).

The advantage over other coating techniques is that EHS can produce particles and fibers of various morphologies (Acatay *et al.* 2004; Dayal *et al.* 2007; Liu *et al.* in press; Liu and Satish 2005; Liu *et al.* 2005; Piperno *et al.* 2006; Ramakrishna *et al.* 2005; Wang and Kumar 2006). EHS applied polymer membranes have shown to favorably alter moisture transmission sensitivity by way of their morphology (Acatay *et al.* 2004; Gleason *et al.* 2007; Ma *et al.* 2005), thus possibly precluding fluorocarbon based

coatings nor the incorporation of nanoclay (Schuman *et al.* 2005) materials, which introduce questionable toxicity and low biodegradability. For example, Gleason *et al.* patented the superhydrophobic performance of electro sprayed and chemical vapor depositions of polyester-based nanofibers, where water contact angles were greater than 150° (Gleason *et al.* 2007; Ma *et al.* 2005).

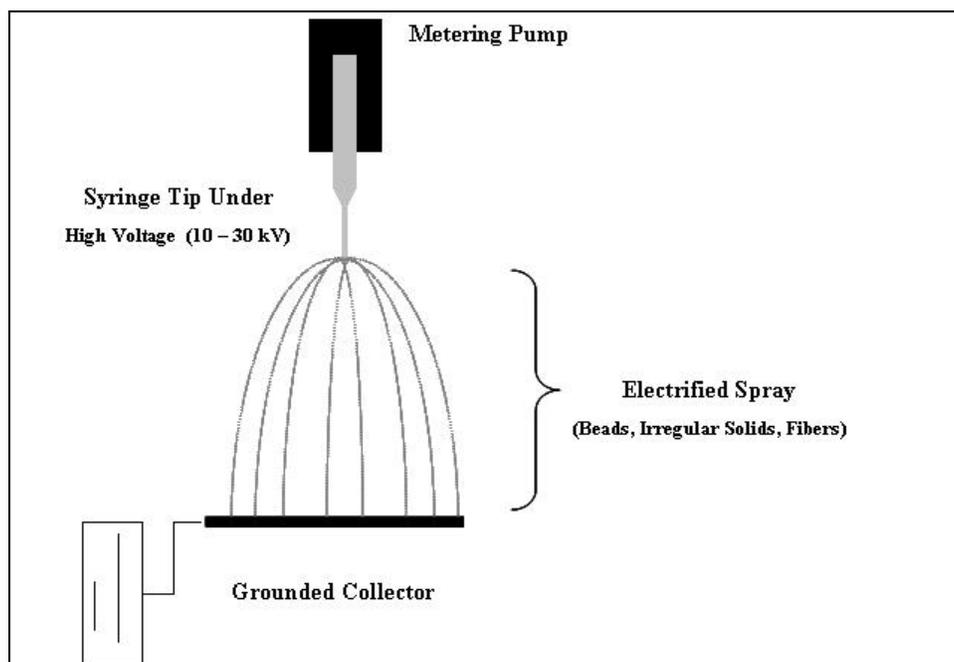


Fig. 1. EHS concept schematic

The present study describes the EHS application of various droplet, fiber, and irregular geometries towards decreasing the water resistance sensitivity of standard unbleached southern US softwood kraft linerboard. Coatings were electro sprayed from either polymer-acetone solutions or latex (polymer synthesized in nanoparticle suspension in water) blended with 2-propanol. Acetone was selected as the solvent of choice, since it has a low surface tension of 22.72 mN/m, which should be ideal for electro spraying at low voltages of 15 to 18 kV. The water soluble/organic co-solvent 2-propanol was combined with latex solutions instead of acetone to prevent flocculation of the latex. An example of electro spraying latex was featured in Stoiljkvoic *et al.* (2007), where spherical polymer particles are preserved in a sheath of water-soluble polymer. EHS is presented here as being capable of producing water-resistant surface nanoscale morphologies without requiring elevated temperature drying, possibly eliminating the energy costs associated with the drying of conventionally applied aqueous coatings. The application of nanoparticles onto the surface of linerboard can produce a water-resistant product with high water vapor transmission. These properties are deemed useful in preventing the spoilage of refrigerated fruits and vegetable, which require transport in water-resistant breathable containers.

EXPERIMENTAL

Linerboard Surface Treatments

EHS solutions consisted of 2 wt% polyvinylidene fluoride (PVDF) (534,000 g/mole, Aldrich) swollen in acetone (from BDH) and poly(methyl methacrylate) (PMMA, 350,000 g/mole, Aldrich) at 3 and 6 wt% in acetone (BDH). Latex blends having 2-propanol (BDH) and deionized (DI) water were prepared using BASF Acronal™ NX 4748 X styrene-butylacrylate latex and commercial Spectra Guard™ 763A and 763B (Spectra Kote Corporation™), acrylic latexes for recyclable water resistant linerboard. 763A and 763B are similar acrylic lattices, with the difference being that 763B when applied in film form has a higher contact angle. Acronal™ latex required stabilization with additional surfactant (Triton® -X 100 by SPI Supplies) to prevent flocculation upon adding alcohol; 10 wt% of Triton® surfactant solution was added to 1g of 50% wt Acronal™ latex and 10g 2-propanol for this EHS solution.

EHS was performed with a voltage between 10 and 18 kV applied to 18-gauge pipetting needles, horizontal and vertical syringe tip-to-collector distances (d, h, respectively) between 5 - 10 cm, and polymer dispensing rates of 1 - 3 mL/hr. Unbleached southern softwood kraft 205 g/m² linerboard obtained from Smurfit Corporation was placed on a grounded flat steel plate electrode when vertically spraying (**Fig. 1**) or alternatively, was secured around a slowly rotating cylindrical 16 cm diameter mandrel when spraying horizontally. Vertical spraying produced a visibly coated disk of 10 to 15 cm diameter. The horizontal spraying arrangement produced a coated band about 10 cm wide on the linerboard wrapped cylinder.

Imaging of EHS prepared linerboard surfaces were observed using Scanning Electron Microscopy (Hitachi S-800 FE-SEM). Surface features were measured via Digimizer Image Analysis Software (by MedCalc Software).

Comparison linerboard samples were also prepared with wax and Spectra Guard™ 736A latex by traditional methods. Waxed linerboard was prepared by immersion in molten wax. Latex was applied using a #7 Mayer wire-wound rod coater followed by drying under IR reflector lamps. Commercially coated paper of the same latex was also received from Spectra-Kote Corporation™. A composite coating consisting of latex (Spectra Guard™ 736A) over a previously applied base coating of Imerys platy kaolin clay, “Astra-plate™”, was also prepared via high speed mixing and applied onto linerboard using commercial production equipment.

Sample Testing

For accurate determination of coating and substrate basis weights, treated and untreated samples were similarly prepared with 2-hour pre-conditioning at 12% relative humidity (RH) and 2-hour conditioning at 50% RH, both at 23°C. This was following conventional TAPPI testing protocol and accounts for the moisture hysteresis sorption – humidity behavior of paper. Conditioning was completed prior to basis weight and coat weight (Equation 1) determinations, water contact angle measurement (via the Pocket Goniometer marketed by Thwing-Albert Instrument Company), Cobb measurements, and determination of the water vapor transmission rate (WVTR). Cobb measurements

(TAPPI method T 441 om-98) were performed using 50 mL of deionized water over a surface area of 25 cm² for 30 minutes. The water vapor transmission rate (T 448 om-97) was determined on areas of 31.6 cm² over 24 hours at room temperature (23°C at 50% RH) and refrigeration conditions (4°C and 80% RH). Equations 1-3 are used to calculate linerboard properties (such as coat weight, Cobb value, and WVTR) in grammage (g/m²).

$$\text{Coat Weight} = \frac{\text{Weight of Treated Linerboard}}{\text{Area of Collection}} - \frac{\text{Weight of Untreated Linerboard}}{\text{Area of Collection}} = \frac{\text{g}}{\text{m}^2} \quad (1)$$

$$\text{Cobb Value} = \frac{\text{Wet Weight} - \text{Dry Conditioned Weight}}{\text{Exposed Area}} = \frac{\text{g}}{\text{m}^2} \quad (2)$$

$$\text{WVTR} = \frac{\text{dish weight after 24 hrs} - \text{0 hr Weight}}{\text{Exposed Area}} = \frac{\text{g}}{\text{day} \cdot \text{m}^2} \quad (3)$$

Pore Size Analysis

Pore size measurements were made to assess the mechanism for moisture vapor transmission in linerboards treated with EHS applied latex and commercial processing methods. The pore size distribution of treated linerboard was determined using the Surface Area and Porosity Analyzer (ASAP 2020) from Micromeritics Inc. Linerboard was degassed for 16 hours under vacuum to remove moisture and gaseous impurities. The isothermal N₂ gas adsorption and desorption facilitated the measurement of pore volume and width.

RESULTS AND DISCUSSION

Moisture Sensitivity of EHS Morphologies

Figure 2 is a SEM micrograph of untreated linerboard at 250 X and 1000 X. Linerboard fibers are shown to have various diameters; the fibrous mat has the appearance of a connected, well-bonded matrix. The water contact angle for untreated linerboard averaged 94° ± 12° from a sampling of 20 measurements. Poly(vinylidene fluoride), PVDF, and poly(methyl methacrylate) (PMMA) were two of several chemistries electrospayed onto linerboard. PVDF was chosen for its known hydrophobicity and high water contact angles. Electrospayed PMMA dissolved in acetone has been shown previously to provide nanostructures (Piperno *et al.* 2006).

Luttringer *et al.* (1991) characterized the microstructure of PVDF in solution as being type I or type II. Solubilized PVDF, or type I, occurs in good solvents like DMF and DMSO. Type II refers to microgel formations of PVDF, which can occur in good solvents and to a greater extent in acetone (Luttringer *et al.* 1991). The application of

electrosprayed PVDF in acetone increased the water contact angle of linerboard up to 142°.

SEM images (Fig. 3) revealed stacked PVDF beads along linerboard fibers. Bead morphologies often result from polymer systems with low solution viscosities and in systems having high surface tension (Ramakrishna *et al.* 2005). The diameter of PVDF beads ranged from 3 - 9 μm . Table I summarizes the dimensions of electrosprayed morphologies onto linerboard.

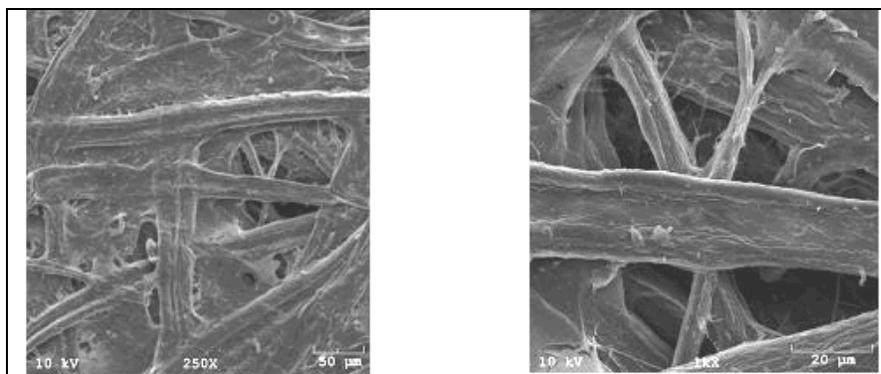


Fig. 2. Untreated linerboard surfaces

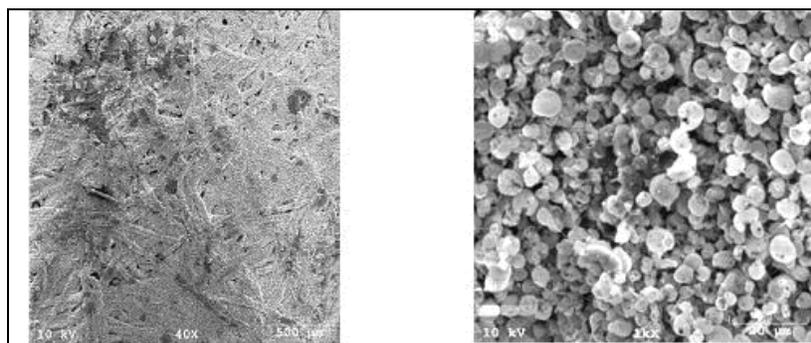


Fig. 3. SEM micrograph of PVDF EHS coated linerboard using 2 wt% PVDF swollen in acetone; electrospraying at 18 kV, 2 mL/hr, h =10 cm. Scale bars are 500 and 20 microns.

Fibrous mats were produced from PMMA solutions; however differences between EHS morphologies from PMMA dissolved in acetone (Fig. 4) stem from concentration differences. Spindle-like and continuous filament morphologies were observed at 3 and 6 wt% PMMA, respectively (Ramakrishna *et al.* 2005).

Although the PVDF coating is different chemically and morphology-wise, surfaces of PMMA fibers (prepared from 3 and 6 wt% polymer in acetone) also had high contact angles, 136° and 142° respectively. The high water contact angles associated with EHS prepared polymer solutions are therefore attributed not only to the chemistry of the polymer but also to the roughness produced by nano to micron geometries, as reported in Table I. Although high water contact angles are indicative of hydro-

phobicity, the PMMA prepared samples were not waterproof. Cobb values for water absorption (not shown) were similar to untreated paper. Poor interfacial adhesion between EHS membranes and linerboard was observed.

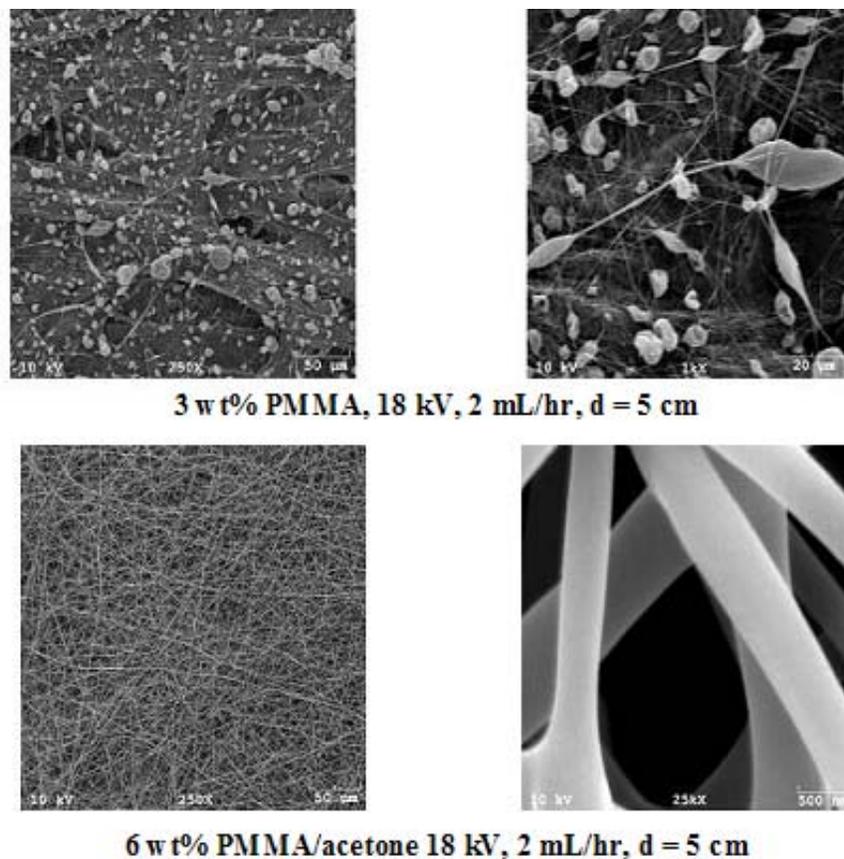


Fig. 4. SEM micrograph of PMMA EHS treated linerboard surfaces at 2 different concentrations of polymer. Scale bars are 50, 20 50 microns and 500 nm respectively.

Table 1. Morphology and Contact Angle of EHS Polymer in Acetone Applied to Linerboard

	Bead Diameter (μm)	Bead Perimeter (μm)	Bead Area (μm^2)	Fiber Diameter (nm)	Contact Angle ($^\circ$)
Untreated	—	—	—	—	94
2% PVDF	3 - 9	8 - 26	4 - 47		142
3% PMMA	9 - 39	8 - 85	3 - 371	94, 250	136
6% PMMA	—	—	—	35 - 807	142

*All water contact angles but untreated linerboard are maximum observed contact angles and not the average.

Linerboard is routinely coated or impregnated with latices commercially for waterproofness. The ability of latex particles to spread into a continuous film has been attributed to film formation at room temperature (RT) from low polymer glass transition temperature T_g , surfactant migration, solvent evaporation, and the minimum film forming temperature (Wicks *et al.* 2007). The T_g of the commercial SpectraGuard and Acronal latexes are quoted by the suppliers to be 0 and 23 °C respectively. Meyer rod coated samples were IR dried to reach a surface temperature of 75 °C for a duration of 180 seconds or more, however EHS applied coatings were left at RT, as drying was unnecessary. Films of these latexes will form at RT, but the optimum performance occurred after several days. In the case of electrosprayed latex blended with 2-propanol, good adhesion to linerboard was observed, in contrast to the polymer/solvent systems. The 2-propanol blended EHS coatings would not rub off in handling. Testing of EHS films would follow after the 48 hour conditioning sequence.

Figure 5 shows sample surfaces of electrosprayed latex coating from 2-propanol solution on linerboard; 2-propanol having a surface tension of 20.93 at 25°C as cited in data handbooks was incorporated to reduce the aqueous coatings (the surface tension of water is 71.99 mN at 25°C). Both samples were prepared via the vertical EHS setup. The concentric patterns were prepared by spraying initially in the center of the linerboard collector; the charged needle was moved out from the center of the rotating collector after being allowed to spray for an allotted time. SEM images of the same samples (**Fig. 6**) show the Acronal™ coating in this case formed a smooth film over linerboard fibers. The visual transparency of the coating (**Fig. 5a**) is attributed to its being a smooth homogeneous coating. Liquid water instantaneously wets this surface. **Figures 7 and 8** of electrosprayed Spectra Guard™ 736A show roughness on the (sub)micron scale that would produce the translucent surface also observed in Fig. 5b. Electrosprayed beads (from the Spectra Guard™ system) have larger dimensions than polymer particles typically dispersed in latex 50 to 200 nm (Oadian 1991).

Spectra Guard™ 736A latex applied in EHS with 2-propanol formed droplets along linerboard fibers (**Fig. 7**). The area of droplets ranged from 1 - 48 μm^2 , with lengths ranging from 0.5 to 1 μm . The maximum water contact angle observed from this sample was 120°. The morphology changed into fractal clusters (**Fig. 8**) when the latex composition was altered and the syringe tip to collector plate distance was decreased $h = 10$ to 4.6 cm. The culmination of nano and micron topography caused the increase in the water contact angle to 135°.

Water Absorbance and Water Vapor Transmission of Prepared Linerboard

Table II, of linerboard electrosprayed with Spectra Guard™ 736 B, gives the coat weights and contact angles of treated linerboard; these samples were electrosprayed at 18 kV and with horizontal collector distances of 5 cm. Contact angles dropped from the 120° to 113° upon increasing the applied coat weight to 13 g/m^2 . The drop in the water contact angle at 13 g/m^2 has been attributed to a decrease in surface roughness as coating particles fill open interstices.

The water resistance (in terms of Cobb) for linerboard electrosprayed with Spectra Guard™ 736 B was modeled as a linear function of contact angle and coatweight. Although a synergy between contact angle and water resistance may be expected, the

multiple linear regression analysis indicated that the dependence of Cobb value on contact angle was insignificant for the data set. Figure 9 shows an inverse linear relationship between coat weight and water absorption, as can be expected from Meyer rod coating experience. Cobb values were indicative of a suitably waterproof coating, *i.e.*, less than 30 g/m^2 of absorbed water over 1800 seconds of exposure) were observed at coat weights of 11 and 13 g/m^2 . Interestingly, the coating weight required for water resistance using EHS is comparable to the range required for rod applied smooth latex coatings. The coverage of latex particles appears to have played the dominant role in determining the water resistance.

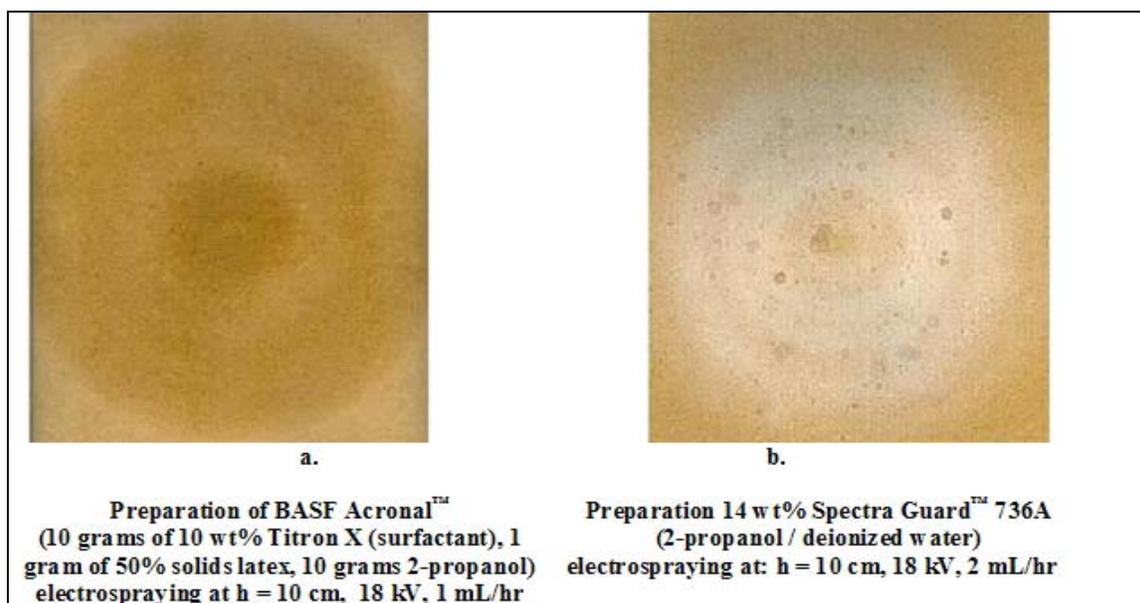


Fig. 5. Photographs of linerboard samples treated with EHS of acrylic latexes with 2-propanol co-solvent. Bottom dimension is 15 cm.

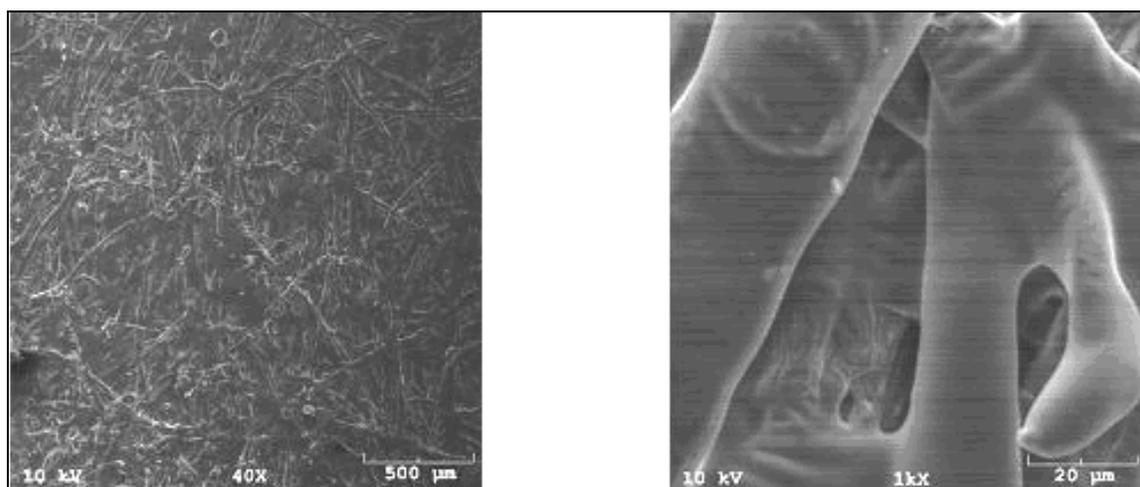


Fig. 6. SEM micrograph of Acronal™ EHS coated linerboard. Note absence of small-scale features.

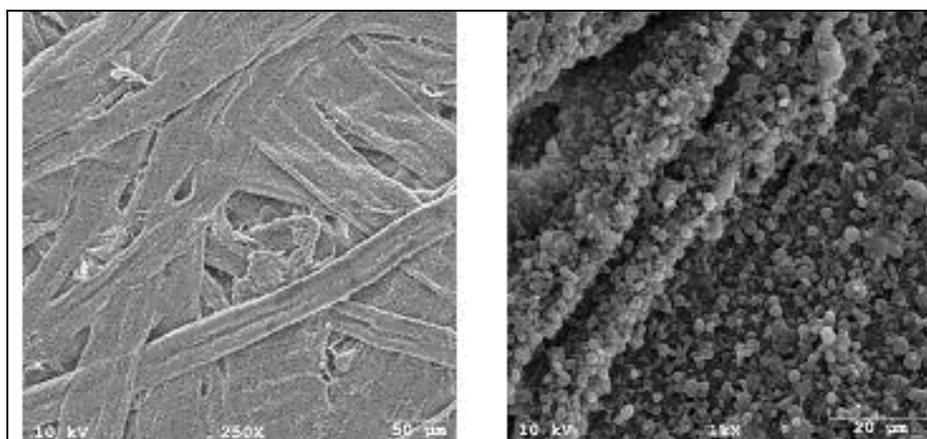


Fig. 7. EHS of 17 wt% Spectra Guard 736A diluted with DI water and 2-propanol (3 mL latex, 2 mL DI water, 1 mL 2-propanol); electrospaying at $h = 10$ cm, 18 kV, 2 mL/hr. Scale bars are 50 left micrograph and 20 microns right.

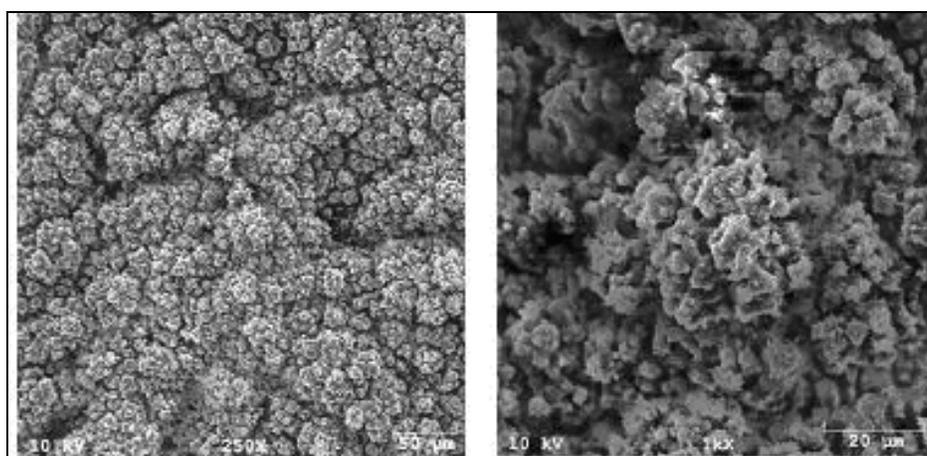


Fig. 8. EHS of 13 wt% Spectra Guard 736A diluted with DI water and 2-propanol (5 mL latex, 5 mL DI water, 5 mL 2-propanol); electrospaying at $h = 4.6$ cm, 18 kV, 2 mL/hr. Scale bars are 50 and 20 microns left and right respectively.

Table II. Data for Linerboard Samples Treated by EHS using Spectra Guard™ 736B Latex/2-propanol

Width (cm)	Length (cm)	Untreated (g)	Treated (g)	Basis Weight (gsm)	Coating Weight (g)	Apparent Coating (gsm)	Contact Angle (°)
7.10	51.8	7.465	7.513	204	0.048	1.2	124
7.05	51.8	7.575	7.766	213	0.191	4.9	127
7.00	51.8	7.319	7.739	213	0.420	11	122
7.05	51.8	7.659	8.177	224	0.518	13	113
7.85	51.8	8.297	8.857	218	0.560	13	—

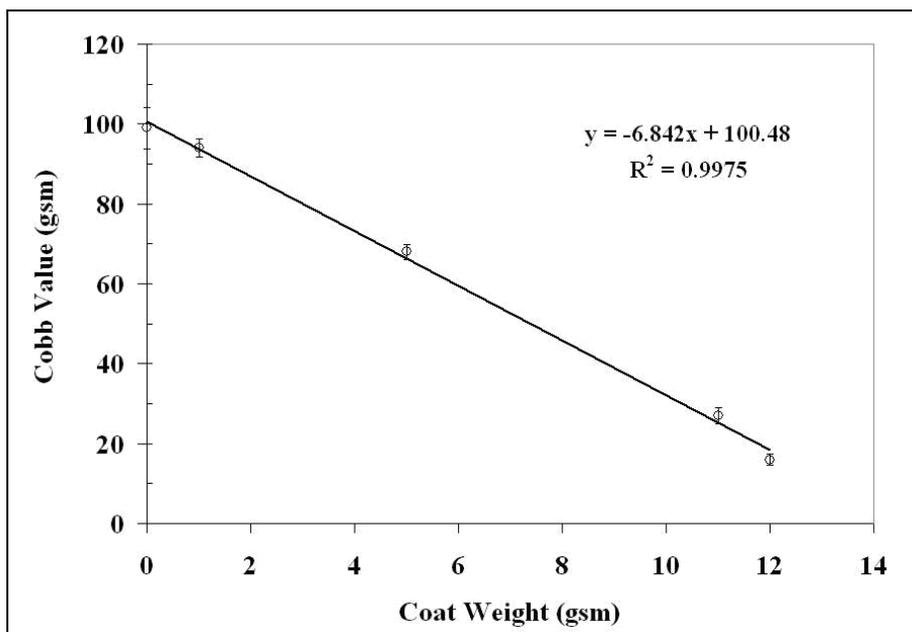


Fig. 9. Effects of EHS applied Spectra Guard[®] 736B/2-propanol coat weight on 1800 s Cobb value

Comparison of EHS with Other Water-Resistant Surface Performance

Linerboard treated with wax, latex, and latex/clay, all considered to be water resistant, were compared for their water and moisture absorption properties. Wax coated linerboard had the best water resistance, as indicated by 0 g/m² Cobb value (Fig. 10). Interestingly, the smooth coating of wax had a water contact angle similar to the electrospayed linerboard that had a total basis weight of 224 g/m². The hydrophobic character of wax and the comparatively reduced roughness of the EHS 13 g/m² coating is likely the cause of similar water contact angles. The electrospayed linerboard sample with total basis weight of 224 g/m² had water resistance most similar to latex treated linerboard prepared via traditional methods.

Traditionally applied waterproof coatings display low water vapor transmission simultaneously with water resistance; such behaviors are evident in Figs 10 - 11. Indeed, no water vapor transmission was detected for the wax-treated sample. Latex applied via traditional processes also show low WVTR rates of less than 100 g/m²/24 hrs. However, the electrospayed latex sample with a coat weight of 13 g/m² (Table II) had a substantially higher WVTR of 466 g/m²/24 hrs, which was quite comparable to 621 g/m²/24 hrs for untreated linerboard. The latex/clay composite coating showed a much lower WVTR than the electrospayed linerboard. The effects of refrigeration conditions of 4 °C and 80% RH on WVTR were also measured and showed that WVTR for EHS treated board was greater than for untreated linerboard sample in Fig. 11.

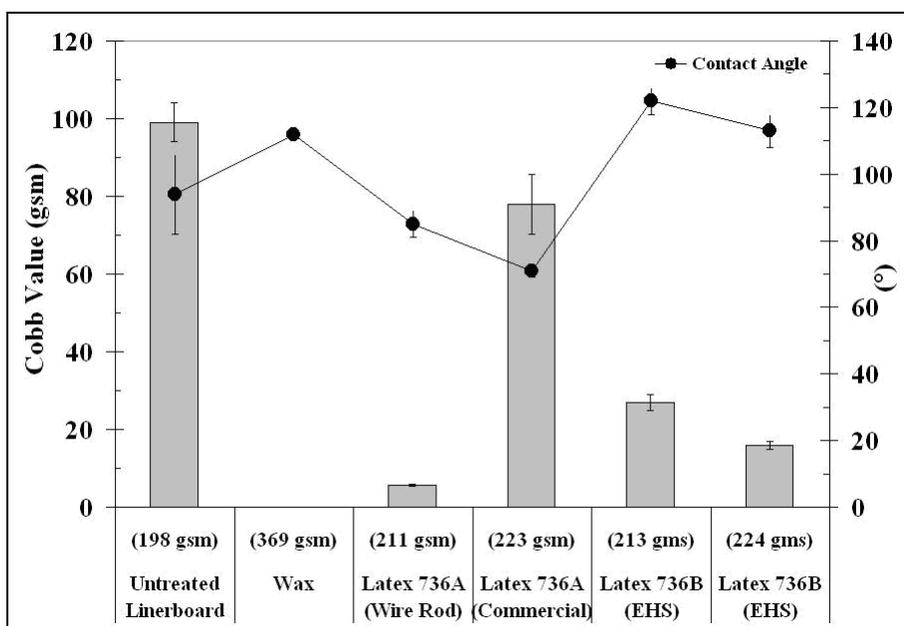


Fig. 10. Comparison summary of water resistance sensitivity of linerboard treated with wax and wax alternatives

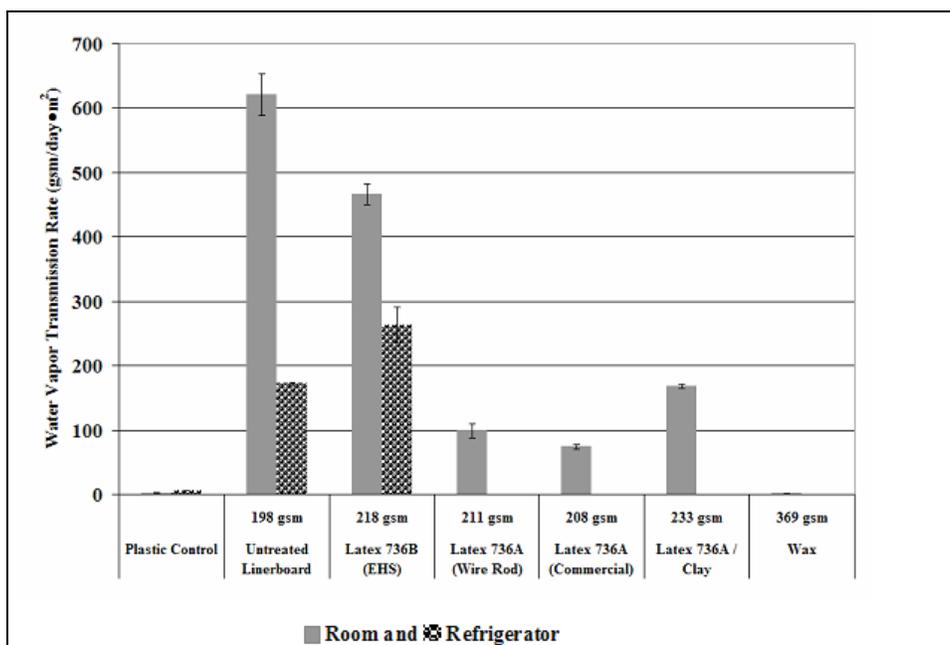


Fig. 11. Comparative summary of WVTR of various coated and uncoated linerboard samples at TAPPI testing standard (23°C 50% RH solid gray bars) and refrigeration (4°C 80% RH cross hatched bars) conditions. A polyethylene terphthalate sheet (Mylar) was used as a control “Plastic Control” to check the integrity of the sealing method.

Pore analysis was undertaken in attempt to understand how water resistant latex coatings applied by traditional means can inhibit vapor transmission, unlike the water

resistant EHS coating. According to **Fig. 12**, latex coatings prepared via EHS and the commercial process had pores on the order of 1 and 2 magnitudes in nano-size.

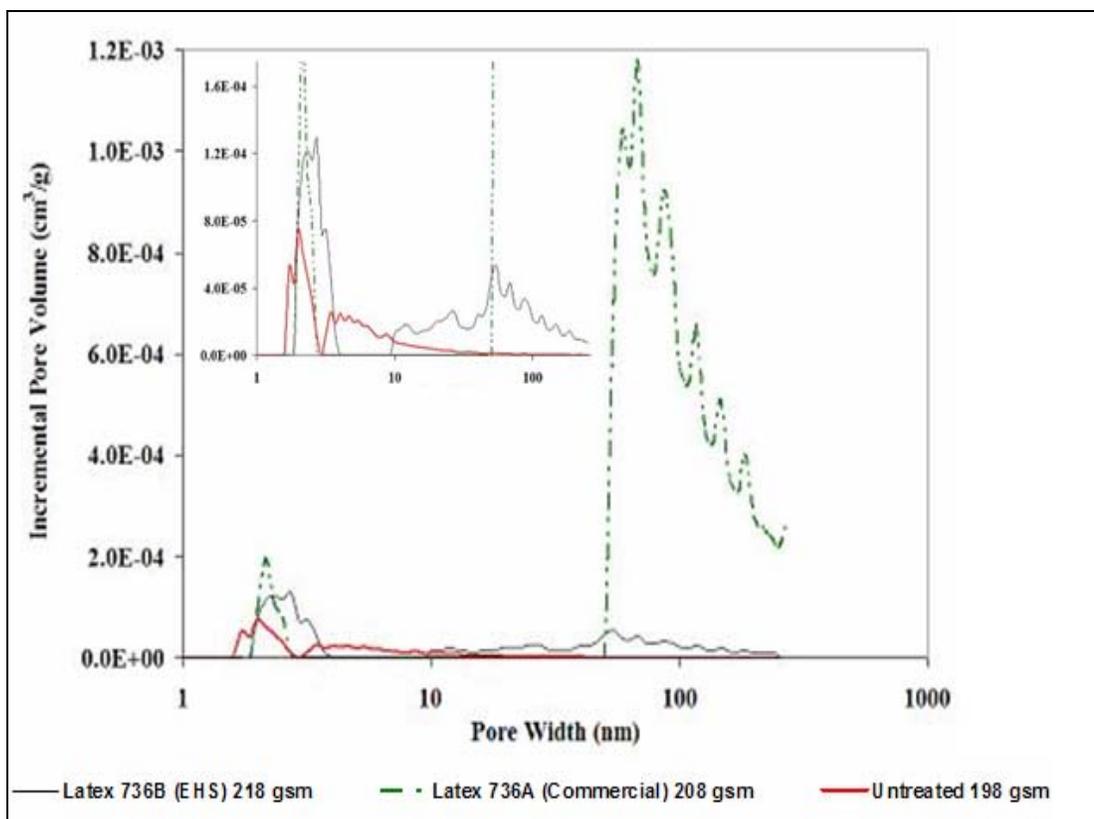


Fig. 12. Pore size analysis of EHS, wire rod latex coated and uncoated linerboard (insert has reduced scale range of incremental pore volumes expanded from 0 to 0.00016 cm³/g)

The commercial latex coating had a greater pore volume than the EHS prepared sample for pore widths of 50 nm and greater, *i.e.* macropore range (Gregg and Sing 1982; Sing *et al.* 1998; Sing and Williams 2004), which is likely attributable to the inevitable presence of air bubbles in the latex when applied in a single pass wire rod coating process. Nanopores having widths of 3 - 50 nm are indigenous to linerboard (Gregg and Sing 1982), and appear to be masked by the commercial latex. Pores of size 10 - 50 nm that were observed in the electrospayed linerboard surfaces are attributed to a stacked latex droplets structure seen in **Fig. 7**. Shown in **Fig. 12**, a distinguishing feature is that the incremental pore volume of the electrospayed linerboard for nanopores and pore widths of 10¹ to 10² nm was much greater than for untreated linerboard. An explanation for these observations may be suggested by the review of molecular adsorbents by Sing *et al.*, where it is shown that small molecules have a greater affinity for pores having dimensions on the molecular scale (Gregg and Sing 1982; Sing and Williams 2004). Moreover, water molecules readily adsorb into nano-slits and moisture sorption is the product of localized adsorption and pore filling (Sing and Williams 2004). A useful comparable example to consider is of Lee and Obendorf (2007), who reported breathable

textile substrates overlaid with electrospun nanofibers. Membrane/textile composites were capable of retaining their water vapor transmission performance up to 2 g/m² of coating. Measurements of pore width and size distribution showed a reduction in pore size diameters, from micron to submicron, with the increasing coatweight. Although WVTR remained unchanged, the air permeability decreased linearly with increasing coatweight. This example supports how pore size also influences the barrier selectivity as well. In our EHS case of the aqueous latex/2-propanol system, we obtained high water resistance and high WVTR, as well as good adhesion of the coating to the linerboard.

CONCLUSIONS

The process of electro spraying polymer onto linerboard facings of pulp and paper corrugated containerboard is proposed as a potential socioeconomic alternative to current commercial processes for waterproofing corrugated containers.

1. Preliminary findings, from our investigation of EHS coatings, suggest simultaneous water resistant performance and high transmission of moisture vapor at room and refrigeration storage temperatures. An EHS latex/solvent formulation under the right conditions was shown to produce a favorable membrane with good abrasion resistance and adhesion to linerboard.
2. Traditional application of latex coatings creates linerboard surfaces that are vapor and water resistant. The observed presence of nanopores in EHS-prepared surfaces can give high water vapor transmission while allowing these coatings to demonstrate acceptable water resistance.
3. In our case, nonporous EHS membranes produced barrier selectivity for vapor over aqueous water. The current results demonstrated on linerboard surfaces are applicable to the packaging of non-durable vegetable crops, which require simultaneous high moisture vapor transmission and water resistance for safe storage and transport.

ACKNOWLEDGEMENTS

We thank the State of Georgia TIP3 for funding this investigation of wax alternatives for use in the pulp and paper industry. Graduate funding was provided through the NSF-IGERT 0221600 known as Technology Innovation: Generating Economic Results (TIGER) between Georgia Institute of Technology and Emory University.

REFERENCES CITED

- Acatay, K., Simsek, E., Ow-Yang, C., and Menciloglu, Y. Z. (2004). "Tunable, superhydrophobically stable polymeric surfaces by electrospinning," *Angewandte Chemie, International Edition*, 43(39), 5210-5213.
- Andersson, C., Ernstsson, M., and Jarnstrom, L. (2002). "Barrier properties and heat sealability/failure mechanisms of dispersion-coated paperboard," *Packaging Technology & Science* 15(4), 209-224.
- Backus, P. (2007). "Competing for cardboard - Smurfit-Stone Container faces competition for limited supply of corrugated containers to recycle," *Western Montana InBusiness Monthly*, Missoula.
- CPBIS. (2008). "Containerboard Industry Review 1970-2000," The Center for Paper Business and Industry Studies, Atlanta.
- Dayal, P., Liu, J., Kumar, S., and Kyu, T. (2007). "Experimental and theoretical investigations of porous structure formation in electrospun fibers," *Macromolecules* 40(21), 7689-7694.
- Gleason, K. K., Rutledge, G. C., Gupta, M., Ma, M., and Mao, Y. (2007). "Superhydrophobic fibers produced by electrospinning and chemical vapor deposition," USPTO, Ed., USA.
- Gregg, S. J., and Sing, K. S. W. (1982). *Adsorption, Surface Area, and Porosity*, Academic Press, Inc., London.
- Lee, S., and Obendorf, S. K. (2007). "Use of electrospun nanofiber web for protective textile materials as barriers to liquid penetration," *Textile Research Journal* 77(9), 696-702.
- Liu, J., Rasheed, A., Dong, H., Carr, W. W., Dadmun, M., and Kumar, S. (in press). "Electrospun micro and nano-structured polymer particles."
- Liu, J., and Satish, K. (2005). "Microscopic polymer cups by electrospinning," *Polymer* 46(10), 3211-3214.
- Liu, J., Wang, T., Uchida, T., and Kumar, S. (2005). "Carbon nanotube core-polymer shell nanofibers," *Journal of Applied Polymer Science* 96(5), 1992-1995.
- Lutringer, G., Meurer, B., and Weill, G. (1991). "Solution properties of poly(vinylidene fluoride). 2. Relation between microgel formation and microstructure," *Polymer* 32(5), 884-891.
- Ma, M., Mao, Y., Gupta, M., Gleason, K. K., and Rutledge, G. C. (2005). "Superhydrophobic fabrics produced by electrospinning and chemical vapor deposition," *Macromolecules* 38(23), 9742.
- Odian, G. (1991). *Principles of Polymerization*, Wiley-Interscience, New York.
- Piperno, S., Lozzi, L., Rastelli, R., Passacantando, M., and Santucci, S. (2006). "PMMA nanofibers production by electrospinning," *Applied Surface Science* 252(15), 5583-5586.
- Popil, R. E. (2006). "Optimizing water resistance of linerboard coatings using pigments," *Tappi Journal* 5(9), 18-26.
- Popil, R. E., and Joyce, M. K. (2008). "Strategies for economical alternatives for wax replacement in packaging," *Tappi Journal* 7(4), 11-18.

- Popil, R. E., and Schaepe, M. (2005). "Comparative evaluation of the potential for wax-alternative packaging coatings," *Tappi Journal* 4(8), 25-32.
- Ramakrishna, S., Fujihara, K., Teo, W.-E., Lim, T.-C., and Ma, Z. (2005). *An Introduction to Electrospinning and Nanofibers*, World Scientific Company, New Jersey.
- Schuman, T., Karlsson, A., Larsson, J., Wikstroem, M., and Rigdahl, M. (2005). "Characteristics of pigment-filled polymer coatings on paperboard," *Progress in Organic Coatings* 54(4), 360-371.
- Sing, K. S. W., Everett, D. H., Haul, R. A. W., Moscou, L., Pierotti, R. A., Rouquerol, J., and Siemieniewska, T. (1998). "Reporting physisorption data for gas/solid systems," *Pure Appl. Chem.* 57.
- Sing, K. S. W., and Williams, R. T. (2004). "The use of molecular probes for the characterization of nanoporous adsorbents. Review," *Particle & Particle Systems Characterization* 21(2), 71-79.
- Stoiljkovic, A., Ishaque, M., Justus, U., Hamel, L., Klimov, E., Heckmann, W., Eckhardt, B., Wendorff, J. H., and Greiner, A. (2007). "Preparation of water-stable submicron fibers from aqueous latex dispersion of water-insoluble polymers by electrospinning," *Polymer* 48(14), 3974-3981.
- Wang, T., and Kumar, S. (2006). "Electrospinning of polyacrylonitrile nanofibers," *Journal of Applied Polymer Science* 102(2), 1023.
- Wicks, Z. W., Jones, F. N., Pappas, S. P., and Wicks, D. A. (2007). *Organic Coatings: Science and Technology*, Wiley-Interscience.

Article submitted: January 5, 2009; Peer review completed: Feb. 23, 2009; Revised version received and accepted: April 13, 2009; Published: April 15, 2009.