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Application of cellulose nanofibril (CNF) as coating on paperboard at moderate solids content and high coating speed using blade coater

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ABSTRACT

Cellulose nanofibrils (CNFs) have the potential to be applied to paper or plastics to produce a good gas barrier layer. Past work has used CNF at low solids content because high viscosity at higher consistencies is problematic. Efficient coating processes are needed to apply CNF at higher solids and significant coat weights to reduce drying requirement and decrease water-paper interactions. A cylindrical laboratory coater (CLC) is used to coat two different forms of CNF at different solids content in double layers. CNF suspension is applied at moderate solids content and a high coat weight ($> 10\,g/m^2$) is possible to be obtained using the blade coater. While others have reported the application of CNF at low solids and moderate speeds, this work shows that it is possible to apply CNF at high speeds (10 m/s) and moderate solids. SEM images reveal that a full surface coverage is obtained even at higher solids content especially when carboxymethyl cellulose (CMC) is added to the coating formulation. The results indicate that an increase around 10–20% for tensile index and about 15% for bending stiffness is obtained. A superior grease barrier property is observed in paperboards with a kit number of 12. An increase of over 300% is found for Hercules sizing results. Air resistance of CNF-coated paperboards increases by a significant amount. Additionally, picking resistance of coated sample is improved with increasing the solids content of CNF coating. The contact angle for water droplets decreases for CNF-coated samples over the uncoated paperboards, however for diiodo-methane (a non-polar liquid) an increase in contact angle is observed.

1. Introduction

Nanosized cellulose fibrils have gained increasing attention during the last few years. This interest is driven by the need to produce nanoscale materials from renewable sources [1]. In addition, these materials have unique properties such as low density, high aspect ratio and high specific strength with the ability for chemical modification. Moreover, they have high barrier properties and are biodegradable and sustainable, and nonhazardous. These properties generate intensive research by different research groups to find applications in the production of nanopaper and films, composites and laminates, as well as foams and aerogels [2–8].

Cellulose nanofibrils (CNFs) are one of the key types of nanoscale cellulose discussed in the literature. They are produced using mechanical processes such as high pressure homogenization, grinding, and refining. CNFs are aggregation of fibrils made up of crystalline and amorphous parts with micrometer length and 10–100 nm in diameter [9–12].

In the paper and packaging industry, CNF has received considerable attention due to a number of potential applications as a wet-end additive but also as a coating to enhance the properties of paper and paperboard [1,10,12,13]. Some reasons that motivated the interest in applying CNF in the paper industry include 1) high specific surface area of CNF, 2) high intrinsic mechanical strength together with good flexibility 3) high potential to interact with cellulose fibers through hydrogen bonding and 4) tendency to form a strong entangled network [1]. Many studies have been conducted dealing with the use of CNF as a coating or in coating formulation with the purpose of replacing oil-based materials (polyethylene (PE), ethylene vinyl alcohol (EVOH), etc.) which are normally used in paper packaging industry to improve the barrier properties of paper and paperboard [14,15]. In some studies, CNF was mixed with other biopolymers and coated onto the surface of preformed paper to form a bilayer structure [16–20]. Both approaches contribute to the increase of mechanical and barrier

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properties of paper and paperboard. Beneventi et al. [21] reported that coating of 2 wt% MFC onto the surface of paper leads to the formation of a continuous MFC film that induces a drop of two up to five order of magnitude in the air permeability of coated paper. Aulin et al. [14] studied the oxygen and oil barrier properties of microfibrillated cellulose (MFC) film and MFC coating (0.85 wt%) and reported that the oil resistance property of the coated paper increased with MFC coating. They mentioned that the reduced surface porosity explains the superior oil barrier properties.

The rheology of CNF suspensions is an important issue for any coating operation. CNF has shear thinning and viscoelastic properties [12,22–24]. The shear thinning behavior should make CNF suitable for coating applications [25]. However, still the viscosity of CNF needs to be taken into special account. When the solids content increases, the viscosity increases and can result in coating difficulties [26]. This behavior has forced the application of CNF to be limited to low solids content (1–2 wt%). In this situation, it is difficult to achieve a good coat weight and also surface coverage [25]. In addition, these low solids increase the energy demand in the drying section. In the current study, two types of CNF are used because CNF produced in different methods show different morphological properties, therefore they may show different rheological properties leading to different coating properties [26]. Moreover, carboxymethyl cellulose (CMC) is used for some samples to modify the rheological properties of CNF suspension and improve the ability to coat at moderate solids. Our results from previous work confirmed that the addition of CMC as an additive to the CNF suspension is helpful to increase the solids content of CNF and at the same time resulting in a uniform coating [27].

In addition to advancements in the CNF coating, the methods to coat CNF suspension play an important role. Because of the difference in the coating mechanism of different coating methods, it is expected that CNF at different solids content can be applied and consequently different coat weights can be achieved [1]. Nevertheless, it is not clear which coating technique works better to apply CNF with properties such as high viscosity. Lavoine et al. [25] coated CNF at around 2 wt% produced by a microfluidizer using a size press and bar coating and studied the mechanical and barrier properties of the coated paper. They reported that in the size press after coating five CNF layers, the coat weight remained at 3 g/m^2 and only increased to 4 g/m^2 after ten CNF layers, while for bar coating after five CNF layers a coat weight of 7 g/m^2 was obtained and increased to 14 g/m^2 after ten CNF layers. This difference in the achieved coat weight resulted in variable mechanical and barrier properties. They also mentioned that the mechanical property was damaged due to the successive wetting and drying cycles. Kumar et al. [28] used a roll to roll coating process to coat CNF suspension. The highest solids content used was 2 wt% and a high coat weight (< 10 g/m^2) was obtained. However, the low speed of coating process was mentioned as the most important challenge.

In the current work, a high speed cylindrical laboratory coater 6000 (CLC) is used to apply CNF suspension to the surface of paperboards at moderate solids content. The CLC has been used successfully in different pigment coating studies [29]. Blade coating is one of the most common coating processes in paper and paperboard manufacturing. It is based on the application of an excess of coating on the base paper which is followed by metering of the excess coating away with a blade [29]. The CLC coater used in this study utilizes the short dwell application system. It operates on the principle that the time period when the coating is in contact with the paper is short before a trailing blade removes the excess coating [30]. In this coating process, high shear rates can be achieved at high coating speed to shear the material to low viscosities [28].

The present work aims to investigate CNF coating properties at moderate solids content (higher than 2%) applied using a blade coater with the purpose of improving the structure, mechanical and barrier properties of paperboard for applications in packaging industry. Furthermore, the effect of two different types of CNF at different solids content (to achieve different coat weights) on CNF coating properties in blade coating process is reported. For some samples CMC as a rheology modifier of CNF is used as well. To the best of our knowledge, this is the first work in which two types of pure CNF at moderate solids content and high speed of coating along with CMC are coated on base boards using blade coater.

2. Experimental

2.1. Materials

The CNF used in this work was produced at the University of Maine‘s Process Development Center from bleached softwood kraft pulp. Two forms of CNF were prepared: the first, refiner produced CNF (rCNF), which was produced using a disk refiner in a two-stage process as described by others [31]. There was no chemical or enzymatic treatment; therefore CNF produced has no surface modifications. The consistency was around 3 wt%. The second, ground CNF (gCNF) was produced by circulating the rCNF in an ultra-fine friction grinder (Masuko Super masscolloider, Model: MKCA6-2, Japan) for two hours. It was prepared at 1.5 wt% consistency. In both CNF suspensions, the solids content was adjusted by the addition of deionized water or using a laboratory centrifuge (Sorval RC 6 plus, Thermo Electron Corporation, USA). Carboxymethyl cellulose (CMC, MW = 450,000 g/mol, degree of substitution = 0.7) was obtained from CPKelco (Atlanta, USA). It was supplied as dry powders from which a solution with a CMC content of 1.5 wt% was prepared by mixing the CMC powders with deionized water while stirring at 600 rpm for 3 h at room temperature. After the preparation of CMC solution, it was added to some CNF suspensions.

2.2. CNF suspension characterization

To characterize the morphology of CNF, Field Emission Scanning Electron Microscopy (FE-SEM) was used (Zeiss, N vision 40, Germany). An accelerating voltage of 3KV and 3 mm working distance were applied. In addition, a countertop ezAFM atomic force microscope (AFM, NanoMagnetics Instrument, Oxford, UK) was used to determine the physical properties (roughness) of the produced CNF layers.

2.3. Coating process

To coat CNF suspension on the surface of base paperboards (200 g/m^2 bleached wood-free paperboard) a Cylindrical Laboratory Coater 6000 (CLC) (Weyerhaeuser, Washington, USA) was used. The CLC includes a rotating drum which holds a sheet of base paper to be coated and a single moving coating pond. To adjust the position of the blade and the whole pond to the backing roll, the pond micrometer is used. IR-lamps are used to adjust the temperature of paperboards just before coating and then to dry the wet coating [29]. In this work, the CLC parameters were optimized to apply CNF through preliminary coating tests and were kept constant. The parameters used were 5 s at 50% power for predrying, 180 s at 60% power for postdrying, 0.3 mm for the gap between blade and backing roll and 10 m/s for the speed of rotating drum. The experimental variables were the forms of CNF (rCNF and gCNF), solids content of CNF suspension (2, 3, and 4 wt%) to achieve different coat weights, and the presence of CMC (4 wt% based on dry weight of CNF determined in preliminary experiences) as an additive. The coating was applied in double layers. The first coat layer was applied on the paper substrate and dried. Then a second coat layer was applied on the top of the first layer. After drying, the uncoated and coated papers were calendered. The conditions for calendering were: line load of 70 kN/m, speed of 7 m/min and 1 nip. All samples were conditioned at 50% RH and temperature of 23 °C for at least 48 h before testing.