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Thermal modeling of vacuum web coating

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Abstract

The paper presents an analytical model for the prediction of the substrate temperature in vacuum web coaters. The model is based on the theory of heat transfer between a continuously moving workpiece and a stationary source, or sink, of energy. The investigation concerns the Physical Vapor Deposition (PVD) of a metal layer on a polymer film by means of thermal evaporation, but many aspects apply equally well to sputtering and electron beam evaporation. The contributions to the specific heat load on the web are quantified, and the influence of the heat exchange between the film and the cooling drum is discussed in detail. After satisfactorily comparing the predictions with available literature results, the model is used as a guideline for a series of experimental tests aimed at determining the influence of the operating conditions on the final quality of the products obtained from vacuum deposition of thick metal layers on thin polymer substrates. The experimental results demonstrate the influence of the mechanical traction of the web on the thermal conductance between the film and the cooling drum.

Keywords: Vacuum coating; Web coating; Thermal modeling; Thermal evaporation; Moving workpieces; Web tension

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1. Introduction

Polymer webs. i.e. thin polymer substrates with considerable flexibility, when coated with metal layers offer consumers the combined advantages of metal and plastic films. The list of substrates includes, but is not limited to: PE (polyethilene), PET (polyethylene terephtalate), PP (polypropylene), CPP (cast polypropylene), BOPP (biaxially oriented polypropylene). The list of coating materials includes, but is by far not limited to: aluminum, copper, silver, nickel, cobalt, zinc [1]. The metallized polymer webs have electrical, optical and gas barrier properties similar to metal foils, but can be thinner than many available metal foils. Therefore it is not surprising that metallized polymer webs are used in a continuously growing number of situations where high electric conductivity, high barrier properties or, simply, striking appearance are required. Applications include, for example,

- electric capacitors,
- gas, light and UV barriers for flexible food packagings,
- thermal radiation screens for building envelopes,
- reflective coatings and
- decorative wrappings.

Physical Vapor Deposition (PVD) is the most reliable technology for the deposition of metal coatings on thin substrates, and the PVD process based on thermal evaporation is the most economical choice for several large scale productions [1]. The process takes place, at operating pressures of the order of 4×10^{-2} Pa, in electrically heated ceramic crucibles, continuously fed by a wire of pure metal. In the crucibles, the melting bath is brought to a temperature high enough to ensure the design rate of metal evaporation. The vapor streams, emerging from the crucibles, are directed towards the moving web where the condensation process takes place. In many instances the key to the success of a product is the possibility of depositing a relatively thick layer of a highly conductive metal on a thin film (see, for example, Ref. [2]). The task is a challenging one,

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Nomenclature

A	area, m^2
F	view factor
h	enthalpy, J/kg
H	thickness, m
l	mean free path, m
L	length, m
$\dot{m}''$	specific mass flow rate, kg/(m^2 s)
p	pressure, Pa
q	heat flow rate, W
q''	heat flux, W/m^2
T	absolute temperature, K
u	web velocity, m/s
x	axial coordinate, m
α	conductance, W/(m^2 K)
δ	average gap thickness, m
ε	emissivity
λ	thermal conductivity, W/(m K)
ξ	local coordinate, m
ρ	density, kg/m^3
τ'	traction per unit width, N/m
τ''	specific tension, N/m^2

Subscripts

A, B, C, D	defined in Fig. 3
c	cooling
d	deposition
g	gap or gas
h	heat load
l	deposited layer
r	radiative
s	solid
v	vapor
w	web substrate

because a high rate of coating implies that a high latent heat flux is associated with the condensation of the metal. To avoid thermal damages the latent heat flux, increased by the thermal radiation flux coming from the crucibles, must be effectively balanced by a corresponding heat flux from the web to a cooling drum. Polymer substrates, in fact, are very sensitive to thermally induced stresses, which may cause various damages, ranging from the formation of wrinkles to recrystallization (see, for example, Refs. [3–5]).

The prediction of substrate temperature distributions in vacuum web coating processes is a valuable design tool, which can help assessing the feasibility of new plants and reducing heat-related defects in existing plants. The paper presents an analytical model for the prediction of web temperature distributions in PVD processes based on thermal evaporation, but many aspects of the analysis apply equally well to sputtering and electron beam evaporation [6,7]. The main feature of the model is the incorporation of the simplifying assumptions suggested by the vacuum coating literature [6–10] in the general theory of heat transfer between a continuously moving workpiece and a stationary source, or sink, of energy [11]. The major difference with the models employed in the vacuum coating literature, in fact, is the adoption of the Eulerian point of view, typical of a stationary observer, instead of the standard Lagrangian point of view, moving with the web.

Temperature values, predicted by the proposed model, were first compared satisfactorily with literature results [6,8]. The model was then used as a guideline for a series of experimental tests aimed at determining the influence of the operating conditions on the final quality of the products obtained from vacuum deposition of thick metal layers on thin polymer substrates.

The tests were carried out in a vacuum roll coater, especially built for the development of new products. Measured quantities included crucible and cooling-drum temperatures, thicknesses of deposited layers and web tensions. The experimental observations demonstrated that the web tension significantly influences the interfacial conductance between the polymer film and the cooling drum.

2. The process

A simplified scheme of a vacuum web coater, based on the thermal evaporation process, is illustrated in Fig. 1. In the scheme two separate chambers are clearly shown: the winding chamber and the coating chamber, which are connected to different sets of vacuum pumps. The separation allows reducing to a minimum the volume of the coating chamber, where it must be maintained the very high level of vacuum required by the thermal evaporation process. The web is transported from the unwinder (1) to the rewinder roll (4), coming into contact with the cooling

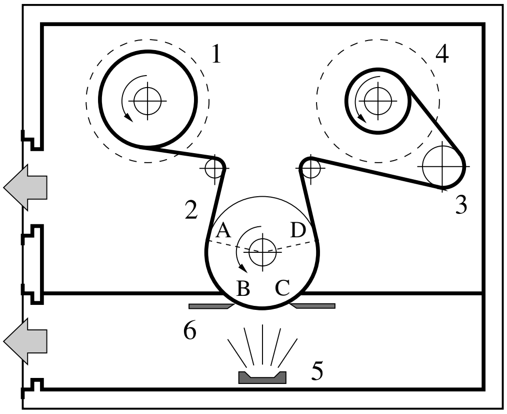

Fig. 1. Simplified scheme of a vacuum web coater with two separate chambers: the winding chamber (top) and the coating chamber (bottom).