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SURFACE STRUCTURE OF PRINTED INK LAYER WITH NANOPHOTONIC ELEMENTS FOR SMART PACKAGING LABELING

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In the article, the theoretical study of the impact of the processes that occur during consolidation of inks with nanophotonic elements on absorbent (porous) and non-absorbent (non-porous) materials, on the morphological characteristics of the surface layer of the resulting printed ink has been conducted. The mechanism of the formation of surface structure of ink layer has been determined, which allows predicting the morphology of the surface structure of the ink layer with nanophotonic elements when printing labels for smart packaging.

Keywords: *ink layer, surface structure, consolidation of ink, smart packaging, nanophotonic elements.*

Formulation of the problem. Smart packaging is new and highly promising on the food packaging market due to its enhanced functionality. Smart packaging allows to monitor the condition of a packaged product during storage and transportation, reporting on the processes that occur inside a packaging by changing some special properties of an active element that is a functional part of this smart packaging. Today unexpired shelf life of products is not a guarantee that the product was stored or transported under proper conditions, was not subjected to the influence of either too high or too low temperatures, solar radiation, humidity, re-freezing etc., and it is still fit for consumption in each individual case. Smart packaging as a category includes a wide range of packaging types and contain active elements based on different mechanisms of reaction to substances that emerge during food aging or spoilage: such active elements can change their optical, mechanical, geometric, electrical properties, and the changes can be fixed visually and/or instrumentally.

The use of nanophotonic elements is quite a promising solution to ensure the functionality of smart packing, using printing technologies that enable fast production of printed smart packaging on industrial scale. Printed images with nanophotonic elements are manufactured using varnish composition based on, for example, nanosized zinc oxide (ZnO), which possess the ability to respond to the presence of substances that are formed during the decomposition of protein products by changing its photoluminescence parameters [1, 2]. These changes can be recorded in visual contemplation (or instrumental reading of values in case of integration in logistic systems) of an active element under ultraviolet radiation and comparing the photoluminescence color and/or intensity of a label with a standard sample. Compliance of photoluminescence color and/or intensity of an active element with a sample indicates the suitability of the product for consumption; minor or significant deviations up to the disappearance of photoluminescence indicate that the product is dangerous to consume. During the printing manufacture of special labels for smart packaging it is necessary to consider packaging surface structure of the resulting printed impression, because this structure directly affects the optical properties of printed ink layer on a printed impression.

Analysis of previous research and publications. The analysis of the literature shows that the question of the formation mechanism of the surface structure of an ink layer of nanophotonic elements is not practically illuminated. There are available literature results of the content of inks with nanophotonic elements [3] and various technological aspects of production of images with nanophotonic elements via printing techniques [4, 5]. Considering these facts, it is necessary to study the processes that occur during consolidation of inks with nanophotonic elements on absorbing and non-absorbing substrates for the purpose of determination of their impact on the morphological characteristics of the resulting ink layer surface, for industrial production of labels for smart packaging.

Aim of the study. The aim of the research is a theoretical study of the influence of processes that occur during consolidation of inks with nanophotonic elements on absorbing (porous) and non-absorbing (non-porous) substrates on the morphological characteristics of the ink layer surface on the resulting printed impression.

Presentment of the main material of the research.

The ink composition was created based on colloidal solution of zinc oxide (ZnO) nanoparticles in ethanol (the mass concentration of nano-ZnO is 0.1%) and polyvinyl-pyrrolidone (PVP) M = 360000 g/mol [3]. The use of PVP allows to achieve the viscosity required for the printing process, and PVP concentration in the solution varies according to the selected printing technique. For screen printing, the mass concentration of PVP in printing ink composition is 12%.

Porous, or absorbing materials (paper without optical brighteners) and non-porous, or non-absorbing materials (polypropylene film and aluminum foil) were selected as substrates (printed materials).

Consolidation mechanisms of printed ink layer on the impression depends mostly on the composition of a printing ink. Ink composition with nanophotonic elements (nano-ZnO) is consolidated as a result of physical process of the solvent (ethanol) evaporation and solidification of PVP.

The time of a solid film formation and consolidation of the ink layer depends on the rate of the solvent evaporation. The rate of the solvent evaporation, in turn, depends on temperature, pressure, surface of evaporation, and ink layer thickness.

It is known that the rate of solvent evaporation from solutions is less than the rate of evaporation of pure solvents. It depends on the nature of the solute, in this case, the rate of evaporation of ethanol from the ink layer on the impression is affected by the concentration of PVP, which varies depending on the used printing technique, and accordingly, the required ink viscosity.

The process of evaporation of the solvent in the case of relatively thin ink film (1.2 microns) occurs from the formed ink film surface, and due to its small thickness the diffusion of the solvent in the deep layers of an ink film will take place relatively quickly. When choosing the thickness of an ink layer, the surface structure of a substrate (printing material) should be considered. When applying an ink composition on rough surfaces it is advisable to correlate the thickness of an ink layer on a printed impression with the roughness of a printing material, for the full coating of micro irregularities of the material by the ink composition. Therefore, the diffusion process of the solvent should be separately considered for ink layers of relatively large thickness (5–20 μm and more), obtained on the abovementioned materials, for example, by using screen printing technique. In the case of relatively thick ink films, the lower diffusion rate of the solvent in an ink layer will have a significant impact on the consolidation of ink layers, which depends on the nature and concentration of a filmmaker (ink carrier, or ink medium) in the ink composition. Therefore, during the evaporation of solvents, surface tension gradient occurs in the film thickness $\Delta\sigma = \Delta\sigma_1 - \Delta\sigma_2$ [6] because of uneven solvent concentration in a surface layer C_1 and a deep layer C_2.

Since surface tension gradient in the film thickness increases with the increase of the difference $C_1 - C_2$ and the difference between surface tensions of a filmmaker (ink carrier) and a solvent. Surface tension of ethanol is 22.8 mJ/m^2, PVP with different molecular weight — 40–42 mJ/m^2. For comparison, water-based inks are characterized by higher values of surface tension as water surface tension is 72.7 mJ/ m^2. Water inks poorly moisten hydrophobic surfaces, so it is preferable to administer alcohols or surfactants (in case of latex inks) to heir composition.

The presence of gradient $\Delta\sigma$ causes the formation of turbulent flows in a solution that create appropriate relief of ink layer surface. When the high viscosity of the ink material in the surface layer is achieved, this relief is fixed in the film as the corresponding pattern [6]. Accordingly, the future morphology of an ink layer surface on a printed impression can be predicted.

The rate of solvent evaporation also depends on the concentration of the solvent vapor in the gas phase. Therefore, to accelerate the consolidation of an ink layer, convective drying (with cold or hot air) can be applied. However, in case of relatively thick ink layers, solvent diffusion rate from the deep to the surface layers of an ink film does not undergo any significant acceleration, resulting in the increase of the surface tension gradient in the film thickness. During too rapid evaporation of a solvent, the consolidated surface layer of an ink film will act as a barrier to solvent evaporation from the underlying layers of an ink film. The result can be a variety of defects in the surface of ink layer on the impression, the appearance of internal stresses in the ink film and the reduction of the strength of the film.

If case of porous (absorbing) materials, the process of absorbing solvent and non-volatile phase by the surface of a printing material happens simultaneously with the process of solvent evaporation from the surface of an ink layer. This phenomenon occurs more rapidly with the greater porosity (absorbance) of paper or cardboard, i.e. with the higher porosity and the lower degree of sizing of the printed material. Thus, during the absorbance of solvents, because of their uneven concentration in the surface layer $C_{1,}$ the middle layer $C_{2,}$ and the deep layer C_3, there is the surface tension gradients in film thickness $\Delta\sigma_{пов.} = \Delta\sigma_1 - \Delta\sigma_2$ and $\Delta\sigma_{глиб.} = \Delta\sigma_3 - \Delta\sigma_2$.directed in opposite directions However, as in the case of non-porous (non-absorbing) materials, the processes of diffusion of the solvent in the middle layers of the film also need to be considered, which, as mentioned above, depend on the nature and concentration of a filmmaker (ink carrier) in an ink composition.

In general, the concentration of extraneous molecules in a solution — for age and, especially, metallic inks — should be considered because it changes the internal pressure of the liquid phase and its gradient. However, the specifics of nanophotonic materials, including nano-ZnO, is the low concentration of extraneous molecules in the layer (up to 0.1%), so their influence in this case is negligible.

Thus, for predicting surface morphology of ink layer on a printed impression in the case of the use of ink compositions with nanophotonic elements, there should be considered the existing dependence between the value of the surface tension gradient in film thickness and the following factors: 1) type of printing material (porous or non-porous); 2) concentration and nature of a filmmaker (ink carrier) in the ink — in this case, PVP; 3) ink layer thickness on the impression; 4) type of intensification of ink layer consolidation on a printed impression. These factors determine the morphology of the surface structure of an ink layer with nanophotonic elements for printed labels for smart packaging.

Conclusions. In this paper, the theoretical study of the formation mechanism of the structure of the surface layer of an ink film during the consolidation of inks with nanophotonic elements on absorbing (porous) and non-absorbing (non-porous) materials is conducted. It is determined that by taking into account the type of printing material, the concentration and nature of a filmmaker (ink carrier) in the ink, ink layer thickness on the impression and the type of intensification of ink layer consolidation on the printed impression, the morphology of the surface structure the ink layer with nanophotonic elements on a printed impression can be predicted for the manufacture of labels for smart packaging.

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СТРУКТУРА ПОВЕРХНІ ДРУКОВАНОГО ФАРБОВОГО ШАРУ З НАНОФОТОННИМИ ЕЛЕМЕНТАМИ ДЛЯ МАРКУВАНЬ РОЗУМНИХ ПАКОВАНЬ

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Здійснено теоретичне дослідження впливу процесів, які відбуваються під час закріплення фарб із нанофотонними елементами на всотувальних (пористих) і невсотувальних (непористих) матеріалах, на морфологічні ознаки поверхні одержуваного фарбового шару на відбитку. Визначено механізм процесів формування структури поверхні фарбового шару, що дає можливість прогнозувати морфологію структури поверхні фарбового шару з нанофотонними елементами при друкуванні маркувань розумних паковань.

Ключові слова: *фарбовий шар, структура поверхні, закріплення фарб, розумні паковання, нанофотонні елементи.*

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