Monte Carlo simulations in OCT for quality inspection of materials

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ABSTRACT

Quality inspection of materials is one of modern applications of optical coherence tomography (OCT) featuring non-invasiveness and high speed required for in-production control of such materials as paper and alumina ceramics. Some of materials to be controlled are characterized by high scattering which can introduce distortions to the obtained OCT images, therefore additional interpretation can be required in order to evaluate material quality. In order to understand formation of OCT images of highly scattering materials samples and evaluate OCT potential for their quality inspection Monte Carlo simulations could be employed. This paper discusses application of Monte Carlo technique for simulation of OCT inspection of paper and alumina ceramics samples. Implementation of Monte Carlo simulation allows to evaluate the effect of OCT setup parameters and material properties on formation of the OCT-images. Multilayer models of paper and alumina ceramics structures are involved in the study.

Keywords: OCT, Monte Carlo simulations, paper, alumina ceramics

1. INTRODUCTION

Optical coherence tomography has found wide area of applications beyond its primary field, medical imaging [1] benefiting from non-invasiveness and ability for real-time high resolution monitoring. The latter feature, in particular, is the key for in-production material quality inspection. It is especially beneficial for quality control in continuing production with roll-based machines, such as paper machines [2] or devices for roll-to-roll manufacturing of ceramic microdevices [3]. The OCT scanner can be situated next to the moving material layer to ensure real-time quality control. However, a limitation for OCT inspection of such materials as paper and alumina ceramics originates from multiple scattering of OCT probing radiation in the studied samples which means that an OCT-image can be not a adequate representation of the samples inner structure. In this respect understanding of OCT images formation of such samples and the role of multiple scattering are required. Theoretical approaches for simulation of OCT-images are hardly applicable when consideration of non-trivial, for example, multilayer geometry is required. In this situation numerical methods for simulation of probing radiation transport in the inspected sample can be employed. Monte Carlo technique is considered as a gold standard for simulation of light transport in highly scattering media [4]. In this paper we consider Monte Carlo simulation of OCT images of paper and alumina ceramics samples performed for understanding formation of the OCT-images and evaluation of potential of typical OCT systems for material quality inspection. The simulated images are compared with experimental ones.

2. MATERIALS AND METHODS

2.1 Monte Carlo simulation of OCT image

Monte Carlo simulation of light transport in scattering media is a statistical technique based on simulation of large number of random photon trajectories in a predefined geometry and further analysis of the obtained results [4]. The input parameters are the distribution of optical properties in the considered medium (scattering coefficient, absorption coefficient, anisotropy factor, refractive index), parameters of the probing beam and detection conditions. OCT A-scan is obtained basing on the calculated distribution of back-reflected photons over the optical travel pathlength that fit the detection parameters of a particular OCT system. Monte Carlo simulations of OCT images is performed by a consecutive step-wise calculation of individual A-scans followed by a further construction of 2D bitmap image.

2.2 Paper samples

Paper sample structure can be represented by a particular stochastic network of cellulose fibers. Enhancing paper quality is usually performed by adding fillers of various sizes to paper pulp during production. Also present in paper samples are fines, which are small parts of fibers. The thickness of forming cellulose fibers typically varies from 10 to 40 μm, while their length can reach several millimeters. Paper samples usually vary in thickness from 50 to 150 μm. In simulation we employ multilayer model (consecutive fiber and air layers) of paper samples with complex boundary geometry mimicking fiber layers [5]. When simulating the effect of optical clearing agents (OCA) on OCT imaging of paper samples the air layers are substituted by the layers of corresponding clearing agents.

2.3 Alumina ceramics samples

Alumina is one of the typical materials for ceramic manufacturing. It is currently considered as a material for micro fluidic devices for micro reactors, fuel cells or medical devices due to its mechanical properties, stability against chemical attack, high temperatures, thermal shock and abrasion. The structure of alumina is characterized by air pores with average size below 1 μm distributed randomly within alumina matrix. In simulations we considered multilayer alumina structures with a laser-machined channel.

2.4 OCT setups

For inspection of paper samples we consider time-domain OCT device developed at the Institute of Applied Physics of RAS (Nizhny Novgorod, Russia) with center wavelength of 910 nm and coherence length of 7.5μm, transversal resolution of 9μm, and the detection angle of 6^0.For inspection of alumina ceramics a Thorlabs 1325nm swept-source OCT with center wavelength of 1325 nm, axial resolution of 12 μm and transversal resolution of 25 μm was used.

3. RESULTS AND DISCUSSION

Experimental and simulated OCT images of paper with and without OCAs are shown in Fig. 1. Their qualitative agreement allows concluding that the proposed model provides reasonably good results that can be used to analyze the formation of OCT images.

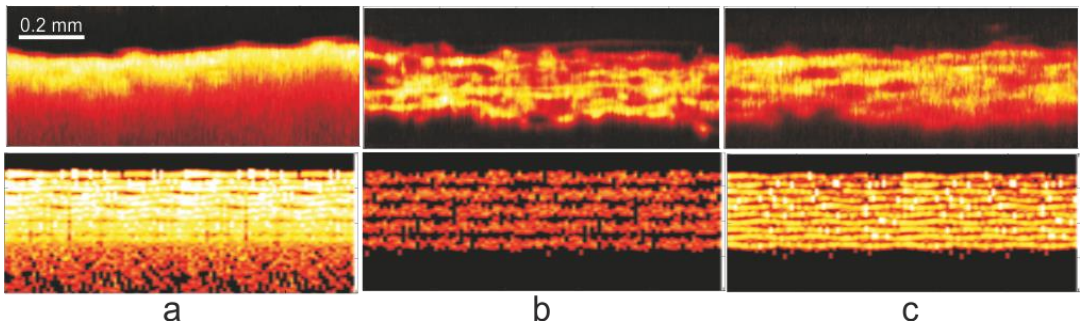

Fig.1. Experimental (top) and simulated (bottom) OCT images of paper samples without optical clearing agent (a), with benzyl alcohol (b), with isopropanol (c).

Application of OCA allows to significantly increase the quality of paper sample inner structure imaging. The effect of OCAs is manifested by decrease in the contribution of multiply scattered photons and clear visualization of sample rear boundary allowing for thickness measurement. Variance in the characteristics of the simulated OCT setup (coherence length and the detector's numerical aperture) in simulations shows that increase of these values reduce contrast of the sample rear boundary in OCT image. Benzyl alcohol is proved to be the most effective optical clearing agent providing the highest rear boundary contrast under the considered conditions.

Experimental and simulated OCT images of multilayer alumina sample are shown in Fig. 2.

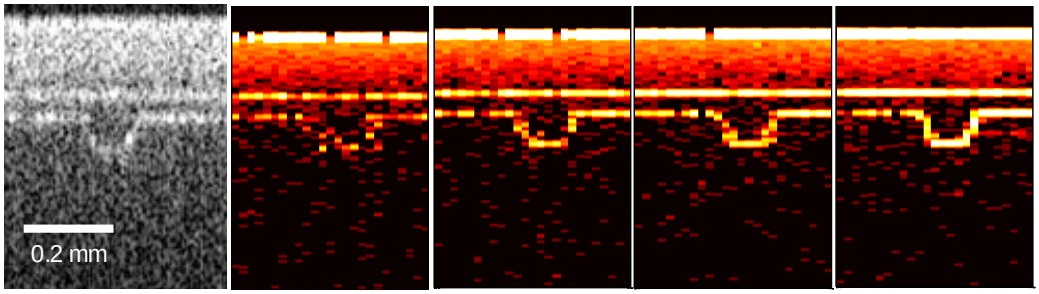

Fig. 2. Experimental (a) and simulated (b-e) cross-sectional OCT images of the stacked alumina layers with embedded microchannel for different RMS roughness of the surface: (b) 140 nm, (c) 90 nm, (d) 60 nm, (e) 30 nm.

We demonstrated the feasibility of using OCT at 1.3 μm for imaging an embedded laser-machined microchannel covered by 100 μm-thick sintered alumina. Monte Carlo simulation allow to simulate the effect of microchannel surface roughness on OCT imaging quality. Variation of the thickness of the upper alumina layer in simulations allows to determine OCT abilities in inspection of multilayer alumina structures.

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