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POLARISATION SENSITIVE OPTICAL COHERENCE TOMOGRAPHY FOR MATERIAL ANALYSIS AND DIAGNOSTICS

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Abstract – We apply optical coherence tomography (OCT) and a modification thereof, namely polarisation-sensitive OCT (PS-OCT), to a variety of problems posed in metrology for material analysis and diagnostics. Among these are imaging of glass-fibre enforced epoxy resin compounds and the detection of dry spots. Furthermore, PS-OCT measurements have been used to measure the birefringence and the orientation of the fast optical axis within test structures: mapping of strain fields of samples under uni-axial and non-uniform external stress and the detection of flow patterns in injection-moulded plastic parts could be successfully demonstrated.

Keywords: polarisation-sensitive optical coherence tomography, material analysis and diagnostics

1. INTRODUCTION AND MOTIVATION

Optical Coherence Tomography (OCT) is a novel non-invasive technique which permits high-resolution cross-sectional imaging of turbid media. OCT employs the partial coherence properties of a broadband light source and interferometry to detect path-length distribution of echoes of light from reflective and backscattering interfaces [1-3]. Since the initial use of OCT for imaging transparent and low-scattering tissues in ophthalmology [1] the application fields have been extended to a variety of tissues in bioimaging and great efforts are currently undertaken for further developments of this technique.

In contrast to conventional OCT, in which the magnitude of the backscattered light is imaged, Polarisation Sensitive OCT (PS-OCT) maps the polarisation state of light within the sample. Thus, additional physical parameters (like birefringence) and enhanced structural information, that is difficult to resolve with other imaging techniques, can be obtained [4-6]. Measurement of birefringence [4], Stokes vectors [5] and simultaneous determination of intensity, birefringence and orientation of the fast optical axis [6] have been reported on biological tissues.

The applications of OCT and its modifications outside the biomedical sector, especially for material investigation and research are so far only marginally touched. Some few developments concern e.g. classical OCT imaging of glass fibre composites for mould flow computation [7] and to detect subsurface defects and cracks in other non-biological materials (e.g. ceramics) [8]. In this study, we extend the classical OCT measurements to PS-OCT for a variety of problems posed in metrology for material analysis and diagnostics.

2. EXPERIMENTAL

For the presented study we used a PS-OCT set-up as schematically depicted in Fig. 1. The beam of a low coherent light source is linearly polarised (vertically) and divided equally into two arms of a Michelson interferometer. In the reference arm a scanning mirror varies the optical path length. The quarter wave plate in the reference arm provides after back-reflection from the mirror linearly polarized light rotated by 45° to its original polarisation direction. The sample under investigation is placed in the other arm and is illuminated by circularly polarized light with the help of a second quarter wave plate.

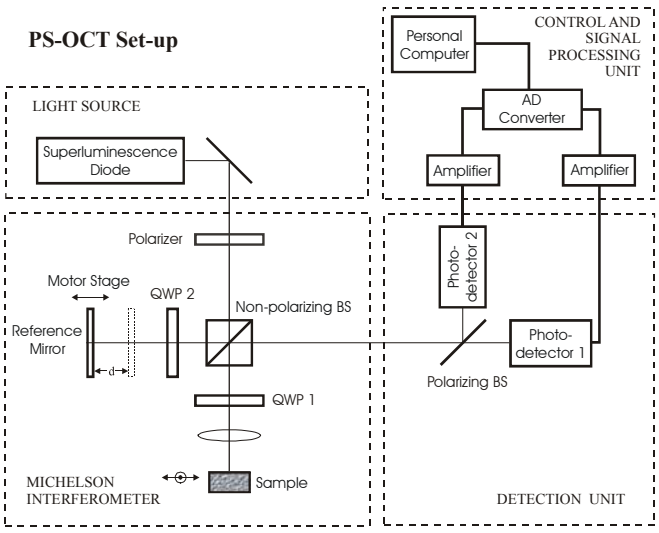

Fig. 1: Schema of PS-OCT set-up with broadband light source, Michelson interferometer, detection and processing unit. Abbreviations: BS, beam splitter; QWP, quarter wave plate

Optical inhomogeneities (e.g. refractive index changes) within the sample reflect and scatter back parts of the incoming light, which is combined with the reference beam at the non-polarising beam splitter of the interferometer. Interference can only occur, if the optical path length of the reference arm equals the path length from the interferometer beam splitter to a reflective interface within the sample. The interference signal (at a Doppler frequency determined by the scanning speed of the reference mirror) is recorded as a function of depth, separately for the two orthogonal polarisation directions (vertical and horizontal) using a polarising beam splitter and two detector units. Therefore, one depth scan (or so-called optical A-scan), carried out by the movement of the reference mirror, provides a one-dimensional distribution of sample reflectivity for both polarisation directions along the z-axis. From the intensity and relative phase of the two interference oscillations the reflectivity, the birefringence and the orientation of the fast optical axis can be simultaneously acquired in a spatial resolved way [6].

The axial (depth) resolution of this method is determined by the coherence length of the used light source [9] and lies typically around 10-20 µm for standard superluminescence diodes (SLD) and amplified spontaneous emission (ASE) sources. By performing A-scans at laterally adjacent sample positions, 2D and 3D information is gained. Therefore, the lateral resolution is limited by the spot size of the focused beam on the sample.

OCT and PS-OCT measurements have been performed by us with a specially for material investigation designed set-up: a 3 mW SLD emitting at a centre-wavelength of 1550 nm has been employed in order to increase the penetration depth in higher scattering materials. The SLD exhibited a spectral width (full width half maximum, FWHM) of about 55 nm resulting in a round trip coherence length of ~ 19 µm in air and ~14 µm in polymer materials, assuming a mean refractive index around 1.4 .

3. RESULTS AND DISCUSSION

A variety of problems in metrology for material analysis and diagnostics investigated by OCT and PS-OCT are addressed in this study.

3.1. OCT imaging of glass-fibre composites

As a first example an OCT cross-section of a 200 µm thick glass-fibre enforced epoxy resin sheet is presented in fig. 2.

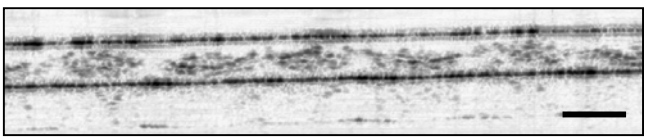

Fig. 2. OCT intensity image of epoxy resin with embedded glass-fibre fabric; bar: 300 µm

The cross-sections of the individual fibre strands of the fabric, as well as a single thread running perpendicular to the strands (woven into them), are clearly resolvable.

Further conventional OCT images of a glass-fibre reinforced epoxy composite are depicted in fig. 3. The sample has been imaged once parallel and once perpendicular to the supporting glass-fibres, clearly resolving the internal structure up to a penetration depth of about 2 mm. The dark irregular regions in the matrix of fig.3 were identified as dry spots and layers, where the glass-fibre structure has not been properly penetrated by the epoxy resin and which are source of delamination and promote fault/crack propagation: especially striking is the imaged double layer fault in the right image of fig. 3.

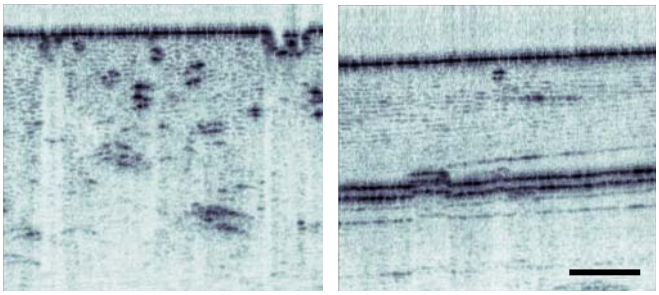

Fig. 3: OCT cross-sections of a glass-fibre epoxy compound material, imaged perpendicular (left) and parallel (right) to the supporting fibre structure; bar 500 µm

As a final example for conventional OCT imaging the cross-section taken from a 200 µm thick transparent lacquer layer on a wooden panel is shown in fig. 4. The thickness distribution of the layer is easily analysable in a non-destructive way. Furthermore, inclusions (filler grains) which are imaged as dark spots within the layer can be identified.

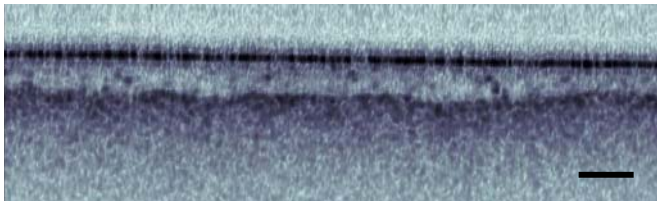

Fig. 4: OCT cross-section image of a 200 µm thick lacquer layer on wood; bar 200 µm

3.2. PS-OCT birefringence imaging

Beside the pure geometrical data supplied by OCT, there is a lot more information achievable using PS-OCT in material research. For example, the corresponding retardation images of fig. 3 (not shown), which were taken simultaneous with the intensity images, exhibited in average a steady (net) increase of the retardation with increasing depths, indicator of a constant birefringence. In addition, features, like the above discussed "dry spots and layers", influenced the retardation crucially. The fast axis orientation images derived from PS-OCT map the orientation of the anisotropy within the material. In the case of the glass-fibre sample presented in fig. 3, they gave the expected 90° relationship for the two principal directions (parallel and perpendicular to the glass fibre structure). By extrapolating these results to short fibre-filled polymers, the simultaneous imaging of the fibre pieces and the

detection of the birefringence of the local (averaged) orientation field of the fibres is feasible, but has still to be experimentally proven.

The capabilities of PS-OCT are best exemplified with a tensile stress experiment performed on a 1 mm thick polyethylene sheet, as presented in fig. 5.

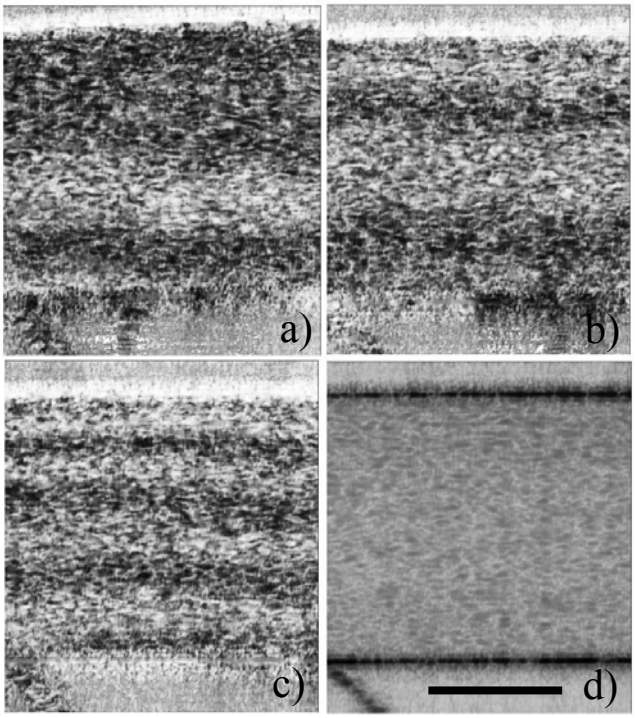

Fig. 5. PS-OCT images of a 1 mm thick strained plastic sheet: a) unstrained, b) 10% elastically strained, c) 20% elastically strained, d) corresponding OCT intensity image; bar: 500 µm

In fig. 5a) we present the retardation image, which is sensitive to birefringence in the material, of the unstrained sheet. In these images the phase retardation between two orthogonal polarisation states of light, corresponding to ordinary and extraordinary rays of the analysing light beam, is mapped to grey levels. Thus, a transition from dark to bright indicates that the phase retardation has increased by 90° over the corresponding distance within the material. A residual birefringence, due to anisotropies in the material caused by the production process, could be detected. The same region of the sample 10% and 20% elastically strained is presented in fig. 5b) and 5c), respectively. Each additional emerging white stripe corresponds to a further increased retardation of 180°. These measurements have been performed with the 1550 nm PS-OCT set-up. Therefore, in the case of the 20% strained image, an averaged total retardation of about 720° over the whole sheet thickness corresponds to a difference of the two orthogonal refractive indices of about $3x10^{-3}$. Fig. 5d) represents the corresponding OCT-intensity image of Fig. 5c) and is practically the same for all cases a)-c), only a decrease of the sheet thickness by a total of 40 µm could be measured.

A further example of strain measurements with PS-OCT is presented in fig. 6, depicting the cross-section of a thin polymer bar under non-uniform stress (bent). The left image is a conventional OCT intensity image, whereas the right image maps, spatially resolved, the birefringence of the sample. One can see, that in the OCT intensity image, there is little internal structure visible (mostly geometrical information), whereas the PS-OCT retardation image exhibits far more details: regions of high strain (compressive and tensile) are easily identified in the birefringence pattern of the mapped strain field.

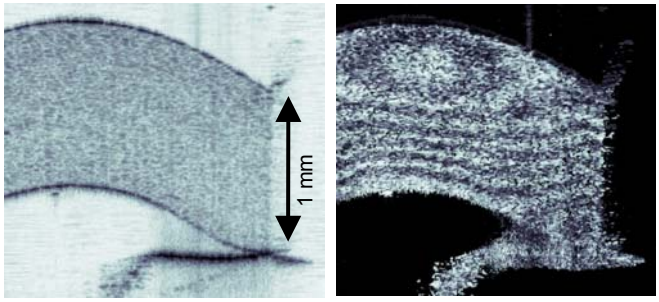

Fig. 6: OCT (left) and PS-OCT birefringence (right) images of a bent plastic part: 1 mm thick polymer bar under non-uniform stress

Full field optical methods are up to now standard stress and strain characterisation techniques. However, there are several disadvantages to take into account. In the case of transmission photoelasticity, a scale model of the part under investigation has to be made in a suitable transparent plastic and coplanar slices of the model have to be placed into a polariscope, which renders the regions of high strain visible as an interference pattern. The fringes in these patterns can be interpreted to give information about the magnitude of the principle stresses that are present in the model. The stresses in the actual component can be derived by applying appropriate formulas on the measured data [10]. Contrary to the latter approach, PS-OCT can directly image the strain pattern in the part itself in a spatial resolved way: it is even easily possible to join consecutive 2D cross-section images to a full spatially resolved 3D data-cube. However, quantification of the PS-OCT data and the implementation in fully automated strain analysis, as it is already the case for well-established photoelasticity methods, needs further developmental work.

As a final example, PS-OCT has been used to analyse in a non-destructive manner whole workpieces and components as demonstrated in fig. 7, where cross-sections of an injection moulded polymer part are presented. In fig. 7 (left) the OCT intensity cross-section of the edge of a injection moulded part is given. Again there is little to no internal structure detectable, whereas the corresponding PS-OCT birefringence pattern of fig. 7 (right) provide in a non-destructive manner spatially resolved information on the internal state of the sample: the sharp edges and corners in the structure caused strong non-uniformities during the injection filling process, detrimental to the part performance. Furthermore, we can identify in a contact-free way regions of high strain. However, a primary task for future developments has to be dedicated to a quantitative determination of strain/stress by PS-OCT.

Nevertheless, one has to keep in mind that only destructive techniques, like layer-removal or hole-drilling,

have been applied up to now for experimentally determining residual internal stress [11,12]. The layer removal technique is based on measuring the curvature of flat samples after thin layers have been removed from the surface. In response to removal of a layer, the sample restores equilibrium by warping. The measured curvature as a function of depth is then used to calculate the stress distribution through the thickness of the sample prior to layer removal. The technique has been the primary method used for plastics but is limited to the measurement of residual stress in flat sheets. Hole-drilling is a more flexible technique as the measurements can be made over a smaller area. The method involves fixing a rosette of strain gauges to the surface of the specimen and drilling a hole precisely through the centre of the rosette. The strains produced at the surface reflect the stress relaxation which has taken place. However, it has been found that the hole-drilling technique produces less reliable results than layer-removal [12]. Compared to these techniques, a promising new way for non-destructive stress/strain determination is within reach using PS-OCT.

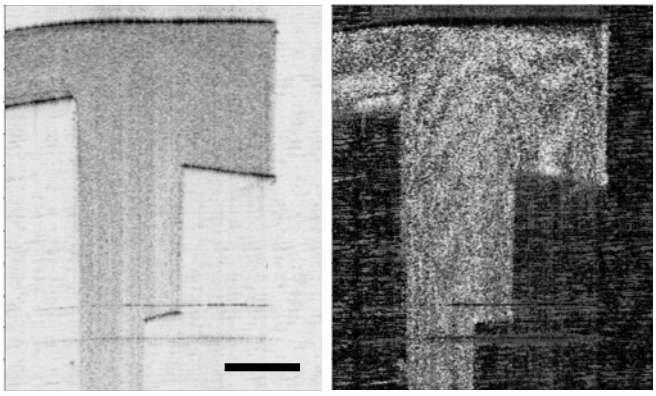

Fig. 7. OCT intensity cross-section (left) and birefringence (right) image of injection moulded plastic part; bar: 1 mm

4. CONCLUSIONS

OCT and PS-OCT have been used to address a variety of problems in metrology and to promote non-destructive analysis and measurement techniques in material science on micrometer scale.

Nevertheless, there are several aspects in PS-OCT which need further research. Especially the quantification of the retardation images and the implementation of PS-OCT in fully automated stress/strain analysis need further evaluation and developmental work.

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