X-ray Grating-based Phase Contrast CT for Non-Destructive Testing and Evaluation

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Abstract
X-ray Phase Contrast Imaging (XPCI) techniques have been receiving increasing attention in the last decade due to the contrast improvement that they offer for weakly absorbing materials such as polymers or biological soft tissues. However, their use in industrial non-destructive testing and evaluation has been up to now marginal, on one hand due to the technical limitations of the initial experimental prototypes and on the other hand, because the applications that are the most adapted to this new contrast mechanism were mostly unknown.

In this paper, we present recent developments made on X-ray Phase Contrast Imaging based on the Talbot-Lau interferometer that allows for high contrast measurements of weakly absorbing objects. The potential for the industrial inspection of fiber reinforced materials (for example impact damage, fiber debonding or porosity) is illustrated with experimental results.

Keywords: X-ray Imaging; Phase Contrast Imaging; Non-Destructive Testing and Evaluation

1 Introduction
X-ray imaging by means of the Talbot-Lau interferometer is gaining more and more interest not only in academic research but also for commercial applications. Indeed, it combines three different contrast schemes in a single measurement: X-ray phase contrast imaging (XPCI), scatter dark-field imaging (SDFI) and conventional absorption X-ray imaging (AB). The underlying physical mechanisms that are responsible for the image contrast are refraction, scattering and attenuation of the X-rays penetrating the sample. XPCI by means of the Talbot-Lau grating interferometer has been attracting increasing attention during the last decade [1-3]. When compared to conventional absorption based radiography, phase sensitive imaging shows substantially increased contrast in weakly absorbing materials, such as plastics or soft tissues. In particular, for biological samples, where dose deposition matters, phase contrast techniques are very promising [4,5]. But also in applications for which the radiation dose is not an issue, phase contrast imaging offers the advantage that light elements, e.g. plastics, can be resolved in a dense matrix. Very often, this is a shortcoming of traditional radiography and tomography, for example in non-destructive testing applications, because the strong absorber prevails and the light element’s signal vanishes.

The Talbot-Lau interferometer enables for SDFI [6,7], which is sensitive to the object’s micro structure such as porosity or microscopic texture. Especially in the domain of non-destructive testing and evaluation of weakly absorbing materials, SDFI is a highly attractive method for visualizing morphology on a submicron or micron length scale below the spatial resolution of the X-ray detector [8]. Therefore, porous materials, fibers in fabrics or composite materials, which cause characteristic ultra-small angle scattering to the X-rays, can be inspected in a very sensitive way. In the present paper, we concentrate on the application of SDFI for non-destructive inspection, testing and evaluation of fiber reinforced polymers (FRP). FRP feature highly oriented fibers and roving of fibers that give

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rise to characteristic (ultra-)small angle scattering which can be detected by SDFI. In the following, the development of instrumentation tailored to this specific application is presented. Moreover, examples of measurements will be shown that illustrate the added value of SDFI for these targeted applications.

2 Talbot-Lau grating interferometer set-up

Fig. 1a shows a schematic overview of the Talbot-Lau interferometer. It is formed by three X-ray transmission gratings combined with a standard X-ray tube source and a digital X-ray image sensor. The three transmission gratings are referred as source grating (G0), beam splitter grating (G1) and analyzer grating (G2). The gratings G0 and G2 have a linear structure of deep lamellae made of a highly absorbing material (Gold). The grating G1, indeed, is a pure phase grating which implies that the lamellae are made of a hardly absorbing material (Silicon). In Fig. 1b a cross-section obtained by scanning electron microscopy (SEM) of an analyzer grating G2 is shown. The periodicity of the Gold lamellae is 3 µm and their depth is 35 µm. All gratings, G0, G1 and G2, were fabricated in the clean room of the CSEM in Neuchâtel by processes combining lithography, deep reactive ion etching (DRIE), wet etching and gold electroplating. Several sets of gratings are available that are designed and optimized for specific measurement conditions such as the X-ray energies.

Our set-up [9-11] is equipped with a conventional X-ray tube source (Comet MXR-160 HP 20), which has a focal spot size of $1 \times 1 \text{ mm}^2$ (EN 12543) and a maximum power of 2 kW. We use a digital, scintillator based detector (Rad Icon Shad-o-Box 2k) that has $2048 \times 1024$ pixels with a size of $48 \times 48 \text{ µm}^2$, each. The field of view is currently limited to $70 \times 50 \text{ mm}^2$ since 100 mm wafers are used as substrate in our fabrication processes. In principle, however, the fabrication processes are compatible with larger wafers. From next year on equipment to process 150 µm wafers will be available at CSEM.

Fig. 2a shows a schematic of the grating interferometer principle. An incident X-ray wave-front is diffracted on the phase grating G1. At certain distances downstream the beam path, an intensity fringe pattern is formed by interference as indicated in Fig. 2a. The distances where theses fringes occur are known as the fractional Talbot distances. If a sample is introduced in the beam path (see Fig. 2b) the incident X-rays are subjected to diffraction and scattering, which causes distortion and blurring of the fringe pattern, respectively. Distortion of the fringe pattern means that locally the position of the fringes has shifted with respect to the unperturbed fringes (i.e. without sample). The relative shift is then proportional to the local deflection angle encountered in the diffraction of the X-ray wave. In addition, the degradation of the relative fringe amplitude is a measure for the amount of scattering. By
means of the so called phase stepping measurement procedure [12] and subsequent Fourier fringe analysis of the data, the values for the lateral shift of the interference fringes and the degradation of the relative fringe amplitude can be extracted. This procedure is applied in a pixel-wise way yielding thus the differential phase contrast image and the scatter dark-field image. Moreover, the attenuation image can also be extracted from this procedure (corresponds to the average fringe intensity over individual pixels).

Figure 2: (a) Schematic overview of the Talbot interferometer principle: By means of diffraction of the incident X-ray wave front on the phase grating G1 a interference fringe pattern is observed downstream the beam. (b) X-rays are subjected to diffraction and scattering, if a sample is introduced in the beam path. Thereby distortion and blurring of the fringe pattern is caused. With the help of the analyzer grating G2 and the phase-stepping technique [12] the distortion as well as the blurring can be quantified yielding the differential phase contrast and the scatter dark-field image, respectively.

3 Results and Discussion

Fig. 3 shows the results obtained from the measurement of a Carbon Fiber Reinforced Polymer (CFRP) plate. The CFRP plate consists of a lay up of 10 plies \([0^\circ/+45^\circ/90^\circ/-45^\circ/0^\circ]\)s with a total thickness of 3 mm which was subjected to an impact of 20 Joules. A photograph of the sample is shown in Fig. 3a. The position of the impact is indicated by the red arrow therein. The sample was provided by the North West Composites Centre (University of Manchester, UK). The pictures labeled with b, c and d in Fig. 3 show the absorption image, the differential phase contrast image and the scatter dark-field image, respectively. While in the conventional absorption image only the largest cracks appear, a better diagnosis can be made thanks to the complementary information contained in the differential phase contrast image and the scatter dark-field image. In particular, the extent of the damaged area is clearly visible in the scatter dark-field image. Indeed, as a consequence of the impact, matrix cracks and fiber debonding appear in the sample, which lead to an increase of the scattering signal. It is possible to detect and laterally localize the position of the impact damage. However, the information on the depth (inside the 3 mm thick slab) of the micro-cracks, fiber debonding, is inherently unknown because they are projected along that direction. Nevertheless, also this information can be accessed if a tomographic measurement is performed.

A tomographic measurement was performed of that sample. As shown in Fig. 4, the slab was step-wise turned around its axis over 360° and for each step a single projection measurement was performed. All three data sets of projection images (attenuation contrast, differential phase contrast and scatter dark-field contrast) were individually reconstructed by applying adapted filtered back projection algorithms[13,14]. On the left hand side of Fig. 4, three equivalent views from the tomographic reconstruction are shown (a: attenuation contrast, b: differential phase contrast and c: scatter dark-field
contrast). The views are slices throughout the slab at the position of the impact and orthogonal to its axis.

![Figure 3: Projection images obtained from measurement of a Carbon Fiber Reinforced Plastic (CFRP) slab of 3 mm thickness. The plate was measured face-on with the Talbot-Lau grating interferometer set-up at CSEM Zurich. As indicated by the red arrow in the photograph (a) the damage caused by the antecedent impact on the sample can only be visualized by SDFI.](image)

The delaminations between the plies can be seen. Apparently, the sensor’s spatial resolution is sufficient to resolve these gaps as well as large cracks in the plies. However, more cracks can be recognized in the SDFI cross-sections that develop in perpendicular direction to the direction of the layers. Since the cracks are neither resolved in the absorption image nor in the differential phase contrast image they must be smaller than the spatial resolution of the image detector. As it was already shown in a previous work [8], SDFI can indeed render structures below the spatial resolution because sub-pixel sized structures cause small-angle scattering that affects the SDFI signal on a pixel-size level.

In Fig. 5 the results from the tomographic measurement of a cylindrical prepreg tube with a dual layer structure (outer diameter: 20 mm, wall thickness: 1.0 mm) are shown. The core layer consists of an uni-directional carbon fibre (CF) prepreg with a thin thread from glass fibres to hold the CF together while the top layer is made of a CF fabric prepreg. For the measurement, the cylinder was turned around its central axis. As for the slab above, measurements of projections were performed for discrete angular positions over 360°. In the top part of Fig. 5 (a-c), the comparison between the three different contrast schemes (AB, XPCI and SDFI, respectively) is illustrated for a cross-section throughout the cylinder. Moreover, the bottom part of Fig. 5 (d-e) shows the same comparison by means of a threedimensional rendering of the tube. Although the disruption following the cylinder barrel is recognizable by all three contrast schemes, the details in the rendering of the barrel’s cross-section are complementary. In particular, in the cross-section obtained from absorption contrast, a pattern of some concentric dashed circles can clearly be recognized, which correspond to the glass fiber that follow the cylinder axis. Although less pronounced, the glass fibers can also be recognized in the SDFI cross-section. Superimposed to these dashed lines, the latter also shows some solid lines roving inside the barrel all around the circumference of the cylinder: They correspond to the carbon fiber roving (prepreg structure). Moreover, in the images (c) and (f) in Fig. 5 (from SDFI) even smaller cracks can be observed that are invisible to absorption and XPCI. SDFI thus provides in this example, a much better diagnosis of the damage in the prepreg tube than absorption contrast. Note that since SDFI relies on the measurement of the ultra-small angle scattering signal, no magnification is required to obtain these images. Thus, contrarily to micro-computed tomography, large samples can be investigated with fast inspection times.
Figure 4: The left side shows a schematic overview of the experimental set-up for the tomographic measurement by means of the Talbot-Lau interferometer. For the tomographic measurement the CFRP sample was turned around its axis over 360°. The sample was an approx. 90mm long slab with a cross-section of $3 \times 25$ mm. The images (a), (b) and (c) are cross-sections through the CFRP slab that are obtained from the reconstruction of the absorption, differential phase contrast and scatter dark-field data, respectively.

Figure 5: (a), (b) and (c) are equivalent cross-sectional views from the tomography of a CFRP tube obtained from attenuation contrast, XPCI and SDFI, respectively. The insets show a zoom in the red square region. The red arrow indicates a microscopic crack that can only be seen using SDFI. (d), (e) and (f), corresponding views form 3D-rendering of the reconstructed data.

4 Conclusion
The results from the presented measurements and examples show that the Talbot-Lau interferometer method is a powerful technique for X-ray imaging in non-destructive testing and evaluation of polymer
and composites parts. The particular strength of that method relies on the combination of three different contrast mechanisms. These are sensitive to different material properties and consequently reveal complementary details. In particular, SDFI is especially well suited for the detection of local irregularities in globally well oriented fiber structures. As shown in the examples, the method can detect micro-cracks and fiber debonding in CFRP caused by impact damage or it can visualize the orientation of carbon and glass fiber bundles and roving. Moreover, the technique is compatible with computed tomography, which allows for three-dimensional imaging of an object. Thus, this novel contrast mechanism shows great potential for the investigation of microscopic features of polymer and composites parts. It is envisioned that this technology will be implemented into industrial products that will offer an alternative to existing NDT techniques for defect analysis or materials characterization of large components at faster inspection speeds.

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References