Phase contrast tomographic imaging of polymer composites

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Abstract

X-ray computed tomography (CT) is a non-destructive method for 3D imaging of inner structure of objects. Phase contrast imaging brings possibility of observation of structures with negligible X-ray absorption or distinguishing of materials with similar X-ray absorption. However, it has been restricted to synchrotron radiation sources due to requirement of spatial coherence of radiation. Along with recent development of X-ray micro and nanofocus tubes and X-ray detectors, phase contrast imaging becomes available also with laboratory sources.
Here, we report on utilization of phase contrast X-ray imaging on RIGAKU Nano3DX tomographic (CT) system. It was demonstrated on a sample of carbon fibres reinforced polyester (PE). In postprocessing, phase retrieval algorithm was applied using ANKAphase for easier segmentation.

Introduction

Using the phase contrast imaging technique, images of samples consisting of low absorption materials have better contrast, moreover materials with similar absorption properties can be distinguished.
In X-ray region, absorption and refraction of X-rays of wavelength λ in a material can be described by means of complex refractive index n, which is defined as

$$n = 1 - \delta + i\beta.$$

Imaginary part β describes absorption properties and it is related to linear mass attenuation coefficient μ by relation $\mu = \frac{4\pi}{\lambda}\beta$, whereas index refraction decrement δ corresponds to phase shift difference of X-ray wave going through material and through vacuum.
For a quantitative information about phase shift φ of X-rays transmitted from the object, phase-retrieval algorithms have been derived [2, 3]. In this work, algorithm used by ANKAPhase software is used. Value of φ is retrieved from each projection using equation derived in [3]. Entering of experimental parameters such as value of δ/β ratio, wavelength of X-rays and source to sample distance is required. Values of δ and β can be calculated for different elements or chemical components [4], but since exact composition of a sample is often unknown, these values have to be estimated. These projections are then processed with standard filtered backprojection algorithm and phase map of an object is reconstructed.
For a long time, phase contrast imaging has been restricted to synchrotron radiation sources or special techniques requiring a spatial coherence of radiation. Today's X-ray tubes have spot size down to units or tens of micrometers and therefore provide partially spatial coherent X-rays, which is sufficient for utilization of phase contrast X-ray imaging with laboratory systems [1]. Single-distance propagation based method of phase imaging is widely used on synchrotron radiation sources. Thanks to its simplicity against the other phase imaging approaches, it is possible to apply this method with modern laboratory CT devices.
In this work, we show a possibility of phase contrast imaging with RIGAKU Nano3DX device within X-ray micro and nano computed tomography at CEITEC BUT. Experimental arrangement of RIGAKU Nano3DX (Fig. 1) provides partially coherent, at the sample stage almost parallel X-rays thanks to large distance between source and sample stage. This arrangement approaches experimental conditions at synchrotron and enables use of ANKAphase as an postprocessing tool, since one of the assumptions of deriving phase retrieval algorithm is that X-rays comming to the sample are parallel.
For a demonstration of phase contrast imaging, a sample of carbon fibres reinforced polyester (PE) was chosen, since it consists of two materials with similar absorption, carbon fibres and PE.

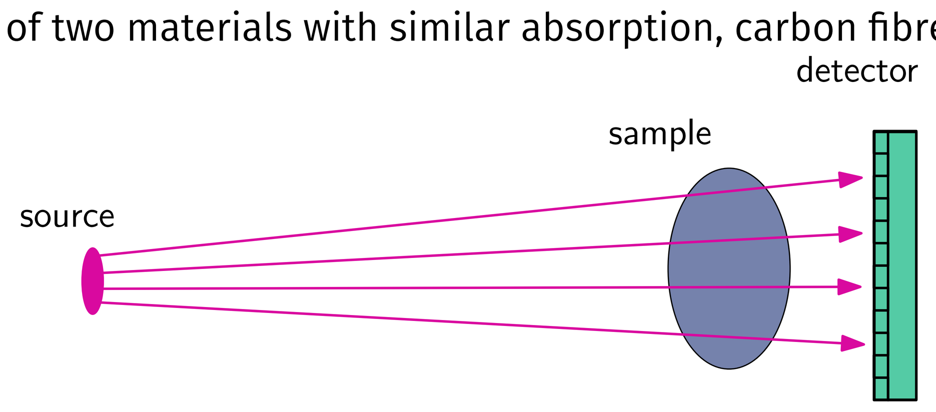

Figure 1: Experimental arrangement of RIGAKU Nano3DX CT device.

Experimental details

Sample from carbon fibres reinforced PE was scanned on RIGAKU Nano3DX device. Parameters of measurement are summarized in Tab. 1. The detection part was an optical head with 20× magnification, enabling the field of view $0.9 \times 0.7\,\mathrm{mm}^2$, and 3300×2500 pixel^2 X-ray CCD camera. The reconstruction was realized using CT reconstruction module within VGStudio MAX. Phase retrieval algorithm was applied using ANKAphase software [3] with $\delta/\beta = 780$ for PE [5].

Table 1: Experimental parameters of measurement of carbon reinforced PE composite on RIGAKU Nano3DX.

Target	Voltage	Current	Exposure time	Projections	Voxel size	Sample to detector distance
Cu	40 kV	30 mA	5 s	800	$(0.54\,\mu\mathrm{m})^3$	1.5 mm

Results

Tomographic section of carbon fibres reinforced PE sample is in Fig. 2. Original section is in Fig. 2a, the section processed with phase retrieval algorithm is in Fig. 2b.
For demonstration of advantages of application of phase retrieval, line profiles over a green line and histograms of detailed views in Fig. 2 are shown in Fig. 3 and 4.

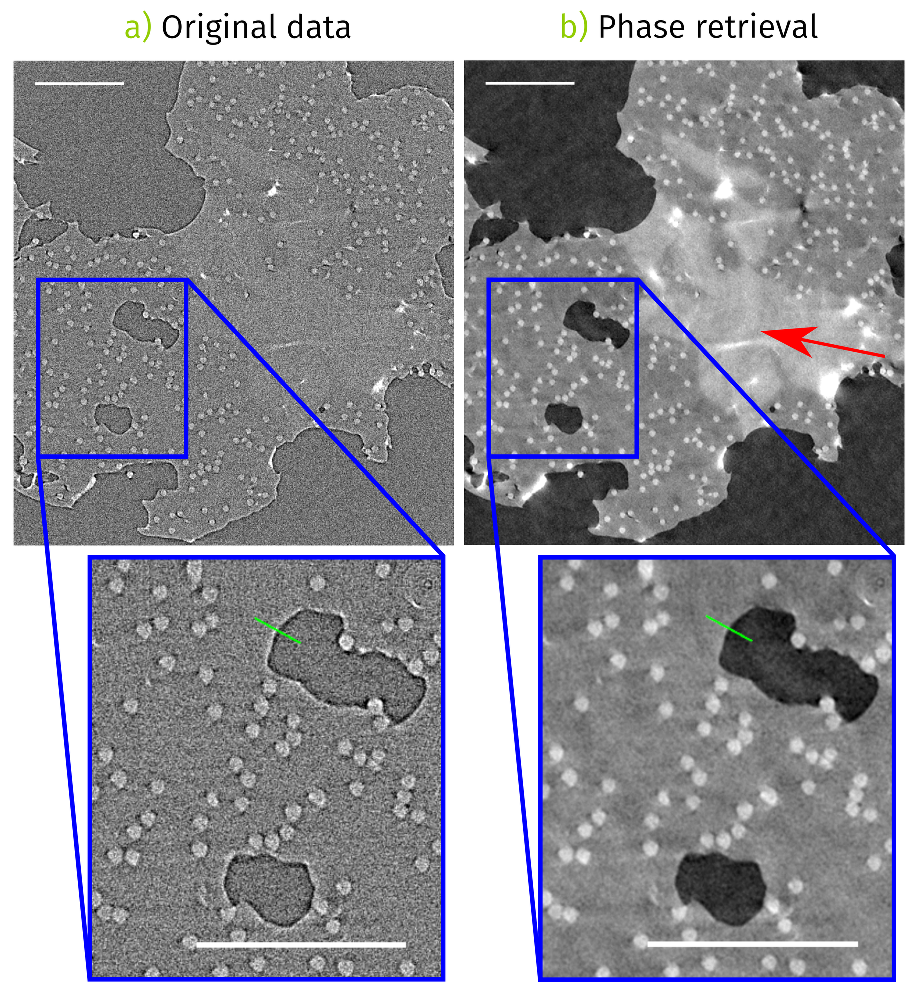

Figure 2: Tomographic section of carbon fibres reinforced PE sample. Length of the scale bar is 100 μm.

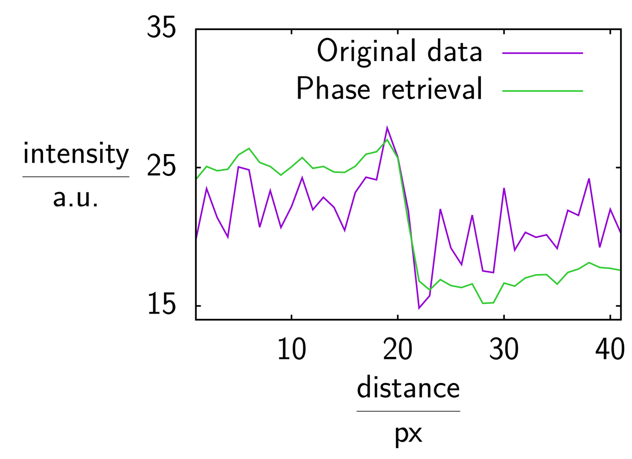

Figure 3: Profiles over a green line in detailed views in Fig. 2.

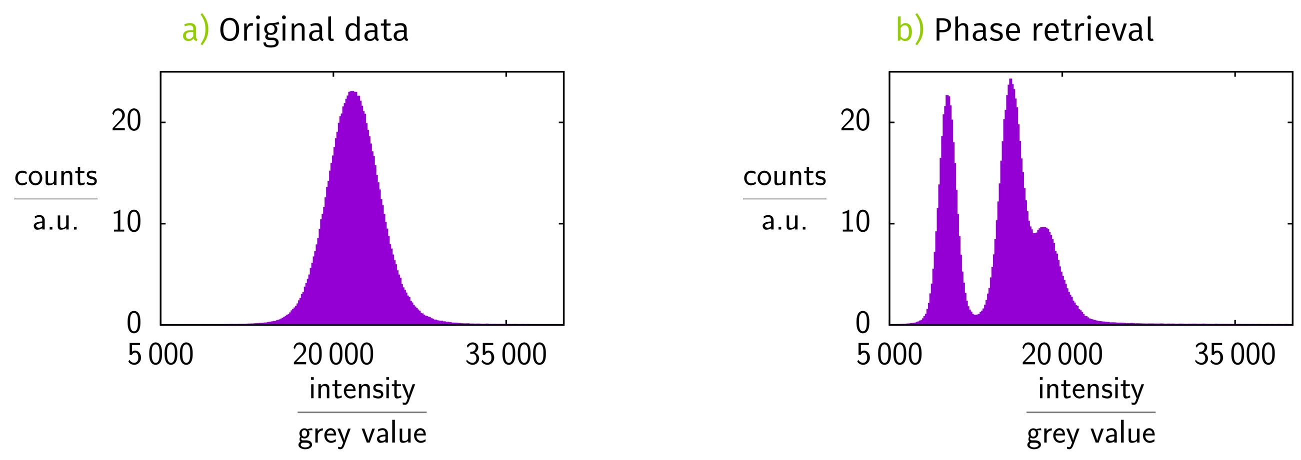

Figure 4: Histograms of detailed views in Fig. 2.

Discussion

Edge enhancement caused by phase effects is visible in a tomographic section of the sample (Fig. 2a). The line profile over a chosen edge highlighted in Fig. 2 by green color (Fig. 3) has a shape typical for images from single-distance propagation-based phase contrast imaging. This fact is surprising since the distance between sample and detector is only 1.5 mm. However, if this distance was set longer, the projection would be blurred due to large focal spot size.
In this image, a segmentation of different parts of material is complicated. There is only one peak in histogram (Fig. 4a), which makes segmentation of carbon fibres and air from PE based on global thresholding according to histogram impossible (Fig. 5a shows the best attempt to segment carbon fibres).
Application of phase retrieval algorithm on X-ray images leads to the CT data with better contrast. Shape of a line profile over the edge has become different (Fig. 3). Shape of histogram has also been changed. There are peaks corresponding to different parts of a sample (air voids, PE, carbon fibres). Now, it is possible to segment carbon fibres by global thresholding, as is shown in Fig. 5b. Moreover, another phase of the studied material, having probably slightly different density, becomes visible (in Fig. 2b pointed by red arrow).

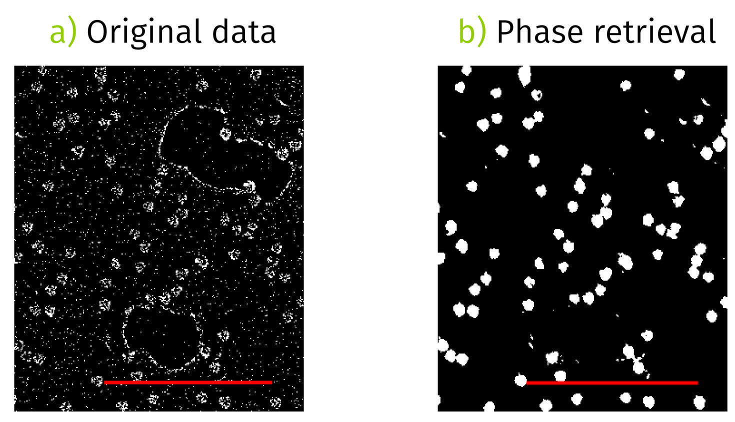

Figure 5: Segmentation of carbon fibres in PE on original data and on data processed with phase retrieval algorithm based on global thresholding according to histogram. Length of the scale bar is 100 μm.

Conclusion

Utilization of phase contrast in CT increases quality of imaging of samples with low absorption or with materials with similar absorption. It requires CT system with partially spatial coherent X-rays. Nowadays, laboratory sources can have spot size small enough to achieve this condition.
In this work, we showed an example of phase contrast X-ray imaging with RIGAKU Nano3DX device on carbon fibres reinforced PE. Edge enhancement typical for propagation-based phase contrast CT imaging is visible, although the distance between sample and detector is only 1.5 mm. Application of phase retrieval appears to be a suitable postprocessing method which makes segmentation easier.

References

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