Synchrotron Radiation-Computed Laminography for Microstructural Imaging of Materials and Devices

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Synchrotron-radiation computed laminography is developed as a novel technique for high-resolution three-dimensional (3D) imaging of regions of interest in flat, laterally extended specimens. It aims at complementing computed tomography for cases where the specimen significantly exceeds the lateral field of view of the detector. A wide variety of applications are expected to profit from the extended 3D imaging capabilities available with synchrotron radiation, including microsystem technology, materials science, palaeontology, art history and life sciences. Examples are presented in the following by microsystem device inspection and materials characterization.

Computed tomography (CT) revolutionized medical imaging in the 1970/80s by providing non-destructive highly contrasted cross-sectional images – compared to projection radiographs where object features at different depths along the transmitted radiation are superimposed – through objects and living patients. It relies on the acquisition of projection datasets at different viewing angles around the object which are then used for reconstruction of one or more cross-sectional slices. Due to progress in imaging detector technology, CT evolved to a general three-dimensional (3D) imaging method towards the end of the past century, with broad applications such as non-destructive device testing in industry, materials research and life sciences. From the 1990s, synchrotron radiation offered high spatial resolutions down to the sub-micron scale and the possibility of using different contrast mechanisms.

Many CT reconstruction algorithms (including the widely applied filtered back-projection algorithm) rely on projection data where the specimen's projection is not truncated laterally. Moreover, the projection data should cover an angle interval of at least 180 degrees (e.g. in the parallel-beam case) of object rotation. When these conditions are violated and extraction of a region of interest (ROI) is inadmissible the image applicability of CT is restricted. This especially applies to objects that are either unique or too precious to be destroyed (by ROI extraction), to laterally extended devices or devices integrated in or mounted onto planar substrates (e.g. in microsystem technology). Even sample extraction can lead to artefacts, e.g. due to heat-generated stresses or due to modification of the boundary by the extraction tool. The latter is especially important in high-resolution imaging (resolution on the sub-micron scale) where the lateral field of view of the detector system generally is restricted and the boundary region affected is proportionally high.

In order to overcome these constraints synchrotron-radiation computed laminography (SRCL) has been developed in collaboration between

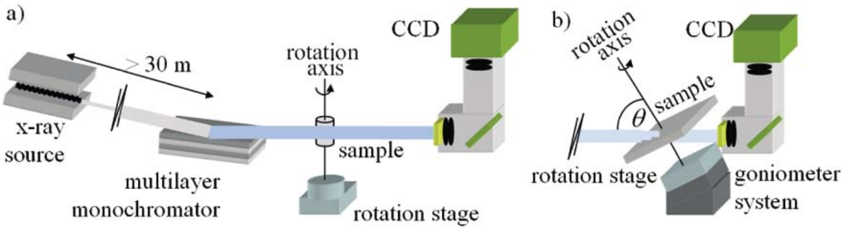

Fig. 1: Comparison between the experimental set-ups for computed tomography (a) and computed laminography (b), as implemented at beamline ID19 of the ESRF.

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[1] L. Helfen, T. Baumbach, P. Mikulík, D. Kiel, P. Pernot, P. Cloetens, and J. Baruchel, „High-Resolution Three-Dimensional Imaging of Flat Objects by Synchrotron-Radiation Computed Laminography", Appl. Phys. Lett. 86, 071915 (2005)

[2] L. Helfen, T. Baumbach, P. Mikulik, D. Kiel, P. Pernot, P. Cloetens and J. Baruchel, "Three-dimensional Imaging by Synchrotron Radiation Computed Laminography", ESRF Highlights 2005, pp. 108–109 (2006)

[3] L. Helfen, A. Myagotin, P. Pernot, M. Di Michiel, P. Mikulík, A. Berthold, and T. Baumbach, "Investigation of hybrid pixel detector arrays by synchrotron-radiation imaging", Nucl. Instr. Meth. A, 563, 163–166 (2006)

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In the following, SRCL is proposed as a standard method for imaging non-destructively laterally extended devices and materials. The scanning scheme proposed is a generalization of the scheme used in computed tomography with synchrotron sources (see also Fig. 1a). At the present stage of development, interesting applications are foreseen in device testing, life sciences, paleontology and many topics of materials science, e.g. in experiments where engineering length scales must be met for external constraints or in situ experiments.

SRCL is based on the acquisition of projection data sets of an object [1,2] rotating around an axis inclined by a defined angle θ with respect to the incident X-ray beam, see Fig. 1. Subsequent computerized reconstruction by a filtered back-projection algorithm yields a 3D image, revealing the microstructure of the object. The experimental setup is compared in Fig. 1 to the one usually employed in synchrotron-radiation CT.

The scanning geometry of CT with an angle of inclination for the rotation axis, θ=90°, can be considered as a special case of SRCL. For conventional (i.e. non-local) CT, however, the object must stay in the lateral cross-section of the beam (and the field of view of the 2D detector system) during rotation. This means that a compromise has to be accepted between spatial resolution and lateral object size. In the case of SRCL, the flat sample can significantly exceed the lateral cross-section of the beam. This allows high-resolution imaging of ROIs in extended flat samples. Scans performed adjacent to each other allow entire devices to be imaged with high spatial resolution.

As an example of microsystem device inspection [3], Fig. 2 illustrates SRCL imaging of a flip chip bonded device. After bump bonding, the flip chip soldered joints are inaccessible to visual inspection. The images show a 3D rendition (a) of bump bonds cut by a plane. Voids in the bump bonds are clearly visible. Such voids affect the long-term reliability of the device when exposed to heating/cooling cycles, e.g. in operation. Images (b) to (d) are reconstructed cross-sectional slices, (b) and (c) through the bump bonds. They exhibit a number of large and smaller voids, the latter predominantly at the interface with the IC's metallization layers (top part in b). The lead-rich phase of the solder is well visible in slice (c); furthermore there are solder splashes near the bump bonds (small satellite spots). Slice (d) highlights a detail of the metallizations and conduction lines on the hidden surface of the IC (see arrows).

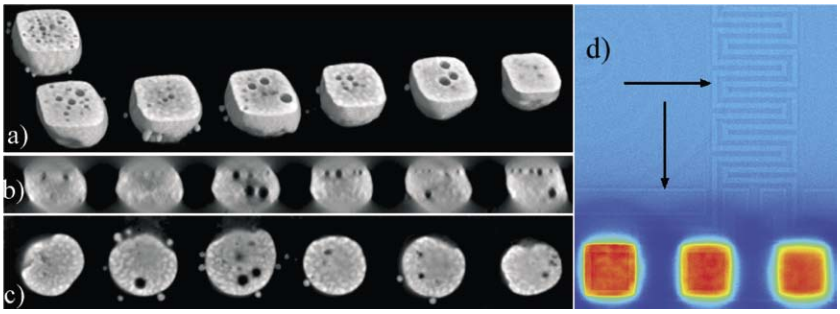

Fig. 2: SRCL inspection of a flip-chip bonded device with a bump pitch of 180 µm: 3D rendition of bump bonds at one corner of the IC (a); two mutually perpendicular slices, perpendicular (b) and parallel (c) to the device surface. Image (d) features a detail of metallisation layers on the hidden surface of the IC. The experiment was performed at ESRF's high-energy beamline ID15 with a voxel size of 1.6 µm and an x-ray energy range between approx. 40 and 60 keV.

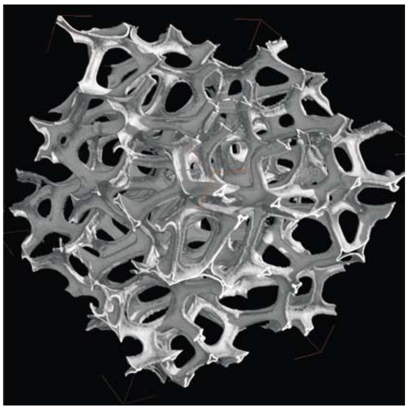

Fig. 3: 3D imaging of a Ni sponge. The depicted cube corresponds to an ROI of 1.3 mm lateral extension out of a sheet of lateral extension of approximately 40×20 mm^2. Voxel size is 1.6 µm and x-ray energy range approx. 40 to 60 keV.

The materials-science example in Fig. 3 presents ROI imaging on a sheet of open-pore nickel foam (Ni sponge). Such sponges are commonly used as electrode materials in batteries and for filtering. SRCL would permit in situ 3D imaging of filtering processes on an ROI in an extended sheet where macroscopic boundary conditions (e. g. concerning fluid flow) could be achieved.

The results reported and the image quality obtained demonstrate the potential of synchrotron radiation-computed laminography. It is a unique tool for non-destructive imaging of flat, specimens extending laterally with spatial resolutions presently down to the micron scale.A dedicated laminography setup has been developed by ANKA and University of Karlsruhe in collaboration with industry. Installed at ESRF's imaging beamline ID19, it allows efficient scanning of large specimens with sizes up to 150×150×5 mm^3. At ANKA, synchrotron laminography will be implemented at the planned undulator beamline IMAGE.