Methodical progress in neutron imaging at PSI

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Abstract

Within this paper we summarize new approaches for the utilization of neutron beams for imaging purposes. Whereas most of the methods are still based on the radiography mode - however now with higher performance with respect to spatial resolution, dynamic range and linearity (obtained often in short exposure time) - the new aspects of using polarized neutrons, the diffracted neutron signal or grating interferometers are linking towards neutron scattering investigations. Many of the new techniques have already found their user community, while some of them are based on users demands themselves. The further progress in the field depends much on the access to useful beam ports at suitable neutron sources.

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1. Introduction

The investigation of the determination of the material distribution in the assemblies can be done by means of penetrating radiation when the transmitted beam component behind the sample is compared to the initial one.

Due to the deviating contrast mechanism in the interaction with matter in comparison to the well-established X-ray technologies, neutron imaging can deliver today competitive, alternative and complementary data, despite of the much lower fluxes and availability of neutron sources compared to X-rays.

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Studies with neutron radiography were focused in the past to film investigations, mainly driven by the requests in non-destructive studies from industry and several academic partners. With the development of highly-sensitive and digital detection methods the acquisition time has been reduced dramatically while the effective beam time usage is increased accordingly. Based on these digital systems which enable studies over a wide dynamic range and with high linearity in the image data, modern quantitative techniques (in first order approximation) like neutron tomography were implemented and used now on routinely basis. Depending on the beam intensity and the intended image quality (dynamic range, signal-to-noise ratio, spatial and temporal resolution), a tomography run can last between a few minutes to many hours.

Since prominent neutron sources are (still) dominated by devices for neutron scattering or for irradiation experiments there are world-wide not many facilities for neutron imaging available to use the full methodical potential. The Neutron Imaging and Activation Group (NIAG) at Paul Scherrer Institut (PSI) operate two beam lines for neutron imaging applications of academic and industrial user’s interest. Access is given to other beam lines too to enable further developments and tests next to the user program.

2. Classification of methods

Fig. 1 gives an overview about the basic, established and advanced methods in neutron imaging. The imaging techniques have been improved and developed dramatically since the first film exposures were done just after World War 2 [1]. This progress is mainly based on the availability of different highly sensitive digital imaging detection systems since about 1995 [2] and the construction of dedicated facilities with best beam performance. This enables a much more intense usage of the neutron beams and allows quantitative evaluations, compared to the only qualitative “picture taking”, coupled with a deeper understanding of the neutron interaction processes using simulation tools.
2.1. Traditional techniques

The basic principle of neutron (or X-ray) radiography is shown in Fig. 2 as a sketch. The “shadow” image on the detector represents the two-dimensional distribution of the attenuated beam after the interaction with the sample material. It is the integral value of all material in beam direction. Therefore, it is impossible to distinguish between front and rear sides of the sample. Since the introduction of digital imaging systems, the distribution is stored as indexed pixel matrix $F_{ij}$. A typical digital system as replacement of films is the neutron sensitive imaging plate technology now [3].

![simplified setup for imaging in transmission mode](image)

*Fig. 2: Neutron Imaging in the radiography mode: principle setting and essential parameters for the image quality determination*

The radiography mode under the condition of a position fixed detector is the basis also for tomography. The sample is investigated from many viewing angles while it is rotated around an axis perpendicularly arranged to the beam. These projections are taken for the reconstruction step, a mathematical process with the 3-dimensional volume (as voxel matrix $S_{ijk}$) as the output [4].

In most cases, the beam is assumed to be quasi-parallel what simplifies the reconstruction and shortens the computation time. If the beam is more conical, the reconstruction algorithm is more complicated and demanding. The number of pixels in the detector has been increase since the beginning from 512 to 4096 now.

This enabled on the one hand higher resolution and more detailed information about the samples, but also induces a higher demand of disc space, as illustrated in Fig. 3. Neutron tomography is a standard tool today, established at several imaging facilities and operated on different length scales (FOV between about 1 cm*1 cm to 40 cm*40 cm and the corresponding effective pixel size as: FOV/pixel number).

The study of time-dependent processes can be separated between “real time” investigations and such of the repetitive approach (stroboscopic mode). Since the number of neutrons in the beam are limited to about 1E7 to 1E8 cm$^{-2}$s$^{-1}$, the count rate per pixel defines at the end the frame rate with useful image information, detectable above the inherent noise level. In addition, the transfer of the primary signal from the detector to a storage device (read out delay) has to be considered too when fast processes have to be studied. The current limits are about 100 fps in the continuous mode [20] and the observation of engines running at 8000 rpm in the stroboscopic mode. The corresponding detection systems are specialized camera devices, amorphous Si flat panels and pixelated semiconductor detectors [5]. Pixel detectors with determined fast readout, high detection efficiency due to absorber-doped micro-channel-plate intensifiers, high spatial resolution due to a centroiding read-out scheme, are promising in particular for studies at pulsed sources in time-of-flight mode [24]. Today, their sensor dimensions are still limited to a few cm$^2$ only.
Fig. 3: The progress in the increase of pixel numbers in the imaging detector also initiated much larger data sets of the reconstructed volumes (dataset size of the tomography volume): 1995 (about 512 pixels in one direction) … 2016 (about 5000 pixels in one direction)

2.2. New options for the user program

All methods mentioned above utilize the whole neutron spectrum as delivered from the source where thermal and cold neutrons are preferred. Under these conditions the highest beam intensity and the lowest exposure time are achieved. However, the integration over the full spectrum delivers only an averaged value for the sample according to:

\[ \Sigma_{\text{eff}} = \frac{\int N \cdot \sigma(E) \cdot \varphi(E) \cdot \varepsilon(E)dE}{\int \varphi(E) \cdot \varepsilon(E)dE} \]  

(1)

The efficient macroscopic cross-section is obtained by weighting with the neutron spectrum \( \varphi(E) \), normalized with the detection efficiency \( \varepsilon(E) \), where \( \sigma(E) \) represent the tabulated microscopic total cross-sections, \( N \) is the atomic density of the material under investigation.

**Energy selective imaging** using narrow energy bands can be applied for better quantification on the one hand, but also to study crystalline structures and their distribution on the macroscopic scale in high spatial resolution. Since the cross-sections of structural materials are mainly determined by the coherent elastic Bragg scattering in the cold energy range, the crystal size and orientation can directly be measured and visualized (see Fig. 4) [6].

If the energy selection is even higher, stress-strain features can be observed on the macro-scale too [7].

For energy selection at beam lines ICON and BOA we have available the following devices: a turbine-type velocity selector with about 10% spectral resolution; a band-pass filter device (TESI [8]) with about 2% resolution and a double-crystal mono-chromator by using pairs of pyrolytic graphite crystals providing about 2% resolution [9].

New options are coming up with the imaging facilities at pulsed sources (RADEN@JPARC (Japan); IMAT@TS, ISIS (UK); NI@IBR2 Dubna (Russia). Using the TOF options with suitable detector performance (e.g. [24]) different kinds of energy selection can be enhanced and exploited. This promising approach should be followed at ESS and SNS by suitable new facilities (ODIN, VENUS).
The method of **neutron grating interferometry** (nGI) was introduced with a setup at the ICON facility in 2005 [10]. The technique is used to derive three signals at the same time: transmission, differential phase-contrast and dark-field. Three gratings are needed to enable the measurements: with an absorber grating $G_0$ in front of the setup a high degree of coherence is initiated. The phase grating $G_1$ behind the sample introduces interference effects in the neutron beam which lead to a self-projection of the $G_1$ structure at the Talbot distance. The interference structure is then analyzed using the analyzer grating $G_2$. Scattering in the sample decreases the coherence of the beam and thus destroys the interference effects (mainly in the dark field). In this manner, features from the ultra-small scattering regime can be resolved locally. A nGI setup is shown symbolically in Fig. 5. Important applications are the study of magnetic domain walls of transformer steel and the visualization of dispersions in the µm particle size region [21].

Most of structural materials have a crystalline structure which scatters the neutrons in a determined manner. Depending on the crystal size, their orientation and the beam conditions, the scattered component of the beam can be used to derive additional information next to that from the transmitted beam. This diffractive imaging approach has been initiated by using a secondary imaging detector, aligned aside to the imaging setup or even in backward direction [11]. The data can be used for the determination of crystal orientation and the degree of single-crystallinity in very simple manner on the macroscopic scale (mm to even cm). This method is still under improvement for even smaller crystals (100 µm grain size) with different orientation, in particular for bulk materials where the X-ray option of this technique will fail in penetration.
2.3. Methodical developments

Neutrons obey magnetic moments with the two spin states (up and down). This property enables interaction with magnetic materials and magnetic fields in a specific manner (Larmor precision). In particular, when one spin state is sorted out and the neutron beam gets “polarized” the method of **polarized neutron imaging** becomes of high interest [12, 13] due to the sensitivity to magnetic properties. For the polarization process, at least two methods are in use: polarized He-3 filters, bender type devices which have each some individual drawbacks. Nevertheless, several configurations for polarized neutron imaging have been built and utilized for interesting studies of magnetic phenomena like super conducting materials, Meissner effect, magnetic field determination and spin state analyses. The beamline BOA will enable further such studies since the initial beam is already highly polarized and the depolarization analysis can be performed with suitable effort soon. First test gave already promising results [14].

**Diffractive imaging** is a new technique where the information about the sample’s properties is derived from the scattered part of the neutron beam. In addition to the “transmission monitor” who is arranged in forward direction just behind the sample a second imaging detector is placed aside where the diffracted neutrons will arrive. Even if this signal is much lower than the direct component, reasonable intensity is collected over a time frame of several minutes. This procedure can be done with the full neutron spectrum (“white beam”). Narrowing the neutron spectrum, some more pronounced reflexes can further be enhanced. In this manner, individual crystal lattice planes are observed. If the grain size is big enough and their orientation fulfills Bragg’s law, they become visible in the secondary detector, as show in the example of Fig. 6.

![Image of diffractive imaging](image)

**Fig. 6:** Turbine blade made from single-crystalline structure (photo –left); transmission image (middle); diffractive image taken under about 90° from the beam direction, indicating the homogeneity of the crystal orientation caused by the growing process [22]

This is demonstrated in the example of a “single crystal” turbine blade (Fig. 6) where the perfection of the crystal can be checked in one projection of the diffracted neutrons measured under Bragg condition with a secondary imaging detector aligned under about 90° with respect to the beam direction. Diffractive imaging is now developed further to more complex coarse grained materials where the experiments are accompanied by the phase analysis on the basis of primary diffraction data. A higher angular coverage as available in the FALCON device at HZB will help for more quantitative investigations.

The trend to **higher spatial resolution** is obvious also in neutron imaging, initiated by the demand of the user community and triggered by the developments in X-ray imaging, pushed by the user community. The limitations in the spatial resolution are caused by the beam divergence, the detector properties and the interaction with the sample (internal blurring). The most common and universal detector configuration is camera based with a neutron sensitive scintillator as converter to measurable light. The project “Neutron Microscope” was initiated to come closer to the physical limit of the method by three key components: ultra-thin, highly sensitive scintillators screen (based on Gd-157), a magnifying optics (5 times) and a highly sensitive camera system with high pixel density. In the test phase a true spatial resolution of about 5 µm was already verified [13].

Today, neutron imaging data on the macroscopic scale between 1 and 40 cm have the same inherent image quality as corresponding X-ray images obtained at tube based facilities. Therefore, configurations have been built to combine the two options of transmitting radiation in one single facility with the aim to have pixel or voxel wise...
option for superimposition. This approach of data fusion is in use at the beam line NEUTRA (thermal neutrons) with the in-line option together with a 320 kV tube [16]. Recently, we finished a setup at the cold beamline ICON by implementing a 150 kV tube [23], arranged perpendicular to the neutron beam. Some first results of studies are shown in Fig. 7.

The data analysis of the data fusion procedure from the X-ray and neutron data can be done in an iterative process where some a-priori knowledge about the cross-section data of the involved materials can be taken as starting points. The larger the difference in the data (as in Fig. 7) the higher can be the probability to distinguish material properties like density and structure.

3. Application fields

The broadening of the methodical options does not automatically provide new user profiles before the feasibility is shown in some pilot tests. In addition, it is important to communicate these new features not only in the neutron imaging community alone, but in the area of potential and already established users. For the moment, the authors have our focus on electro-chemistry (fuel cells, batteries, and electrolysis), metal microstructure, magnetism and porous media. Since neutron imaging is a universal method today, the field will grow further – if the facilities and the beam time are made available accordingly. Further details for the specific new applications are given in the corresponding literature like [25].

4. Effort and challenges

There is the methodical and technological progress on the one hand, but also the shut-down of facilities and sources on the other side. If neutron imaging should be used in the future as a tool for scientific and applied purposes, the existing facilities needs to be upgraded towards a reasonable level and some new “state-of-the-art” facilities be build, based on the current knowledge with respect to the methodical progress. There are candidates around [17] who may need the full support by the neutron imaging community or are powerful enough to perform alone.
5. Outlook

The methodical progress in neutron imaging and the development of a stable user community has been demonstrated at several facilities. Based on these experiences it should be possible to take over the know-how and to serve the local and even international users. Since the neutron sources have their regular shut-down phases, a network for interaction between operators and applicants should be established for an optimized utilization of neutrons for imaging purposes.

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