Recent applications of neutron imaging methods

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Abstract

The methodical progress in the field of neutron imaging is visible in general but on different levels in the particular labs. Consequently, the access to most suitable beam ports, the usage of advanced imaging detector systems and the professional image processing made the technique competitive to other non-destructive tools like X-ray imaging. Based on this performance gain and by new methodical approaches several new application fields came up – in addition to the already established ones. Accordingly, new image data are now mostly in the third dimension available in the format of tomography volumes. The radiography mode is still the basis of neutron imaging, but the extracted information from superimposed image data (like for a grating interferometer) enables completely new insights. In the consequence, many new applications were created.

Keywords: attenuation contrast, digital neutron imaging systems, phase contrast, micro-tomography, engineering diffraction, energy related materials

1. Introduction

The penetration of neutrons through considerably thick structures of materials enables the inspection of objects, assemblies and processes in a nearly non-invasive manner. The transmitted component of the neutron beam is registered with a suitable two-dimensional neutron detector. In comparison to the initial beam distribution, information about content, structure and their development can be derived on the macroscopic scale.

The method of neutron radiography has been initialized since first (radioactive) neutron sources were available (about 1938). First inspections were done already with film using some converter materials (e.g. Ag) [1].

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Since then, both the sources and the detection systems have been developed further and were dramatically been improved. Modern neutron imaging facilities can be found at beam ports of dedicated research reactors or spallation neutron sources now.

On the other hand, digital neutron imaging detectors enable highest efficiency and highest resolution in space, time and contrast/dynamics. Based on the digital output of neutron imaging data, modern image processing tools (including the reconstruction of tomography projection data into the volumes) can be applied. The quantification of the sample content can be performed on higher methodical level, also taking into account the comparison to tabulated cross-section data and by using simulation tools.

While the majority of applications of neutron radiography has been focused in the past to non-destructive testing in complement and as alternative to X-ray methods, the modern approaches also intend to push forward more scientific usages. Nevertheless, also common industrial applications can profit from the methodical progress and the increase in the performance of the neutron imaging systems.

This paper will give an overview with respect to facilities, methods and data acquisition with the aim to focus to best possible applications with scientific and more applied background. It is based on the experience at Paul Scherrer Institut, Switzerland, but can easily be translated to similar facilities at other places.

2. Facilities

In a survey about neutron imaging facilities around the globe, performed by ISNR [1] and IAEA [2], there are currently 48 installations registered. Among them, only about 15 ones can be seen to be “state-of-the-art”, still with differences in the individual performance. All neutron imaging stations have their individual layout and specification and some certification and standardization is required for comparison in the future.

The majority of facilities is situated at research reactors, where the access and usage is dominated by the neutron scattering community, isotope production or irradiation technology. In many cases, not the optimal beam port was given for neutron imaging and compromises needed to be accepted in the beam line layout. Most of the beam lines use thermal neutrons with a Maxwellian spectral distribution around 25 meV, corresponding to 1.8 Å. Since the begin of this century, beamlines with a colder spectrum were also set into operation for neutron imaging purposes (ANTARES, CONRAD, ICON, …). The suit of installations is completed by such for fast (fission) neutrons in the keV and MeV range. Given by the beam properties with respect to size, spectrum, intensity and homogeneity the kind of application is already predefined since the attenuation properties limits the sample thickness with respect to transmission and visibility. With a exposure time of a few seconds at a neutron flux intensity of about $10^7$ cm$^{-2}$ s$^{-1}$ it can be extrapolated which application can be performed with respect to time resolution (real-time, tomography, energy scans, …). It depends on the individual problem which dynamic range in the images is really required, means which acquisition time should be used.

![Fig.1: Schematic layout of a generic neutron imaging facility: the degree of complexity and the particular layout depend very much on the budget and other boundary conditions](image-url)
A simplified layout sketch of a generic facility is given in Fig.1, only summing up the different components, without any focus to scale and importance.

Highest performance can only be achieved at strong large scale facilities (research reactor or spallation source). These installations are built as “user labs”, sharing the performance and beam time among many users from science and industry. The access is either organized in proposal procedures, ranking the scientific values or in a direct payment process for commercial (industrial, museums, …) customers.

3. Methods

The methodical development in neutron imaging follows trends in the X-ray imaging field, but highlights the specific neutron features: higher penetration, specific contrast for several isotopes, use of the magnetic moment, interference features. The higher spatial resolution, the access to the third dimension (tomography) and the study of time-dependent phenomena extend the possibilities of modern imaging much. Since almost all data are now in digital format, the power of image processing is essential for the extraction of best information from raw image data. We give an overview on different methodical aspect in Fig.2.

Fig. 2: Overview on current and future methodical approaches in neutron imaging

The advanced methods: energy-selective imaging, neutron grating interferometry and diffractive imaging need some additional equipment as add-on to the standard imaging setup [2, 3, 4]. They were developed to extract more detailed information from the neutron interaction process, e.g. visualization of the crystalline structure, magnetic domain walls or the crystal orientation. In addition, features of small-angle scattering phenomenon are accessible now for the range of a few µm.
4. The "gap" for neutrons

Caused by the focus on large samples, higher transmission and coarse spatial resolution, the beam at neutron imaging facilities has diameters in the range between a few cm up to about 40 cm. The ratio between FOV and pixel size is given by the pixel number of the detection system in one dimension, which is between 1000 and 4000 currently. The presently highest spatial resolution is on the order of 5 µm [1]. The most common neutron imaging experiments are performed in the “relaxed” resolution range between 20 and 100 µm keeping the exposure time reasonably low.

The challenge and advantage to use neutrons for imaging purposes is still the high contrast for the prominent light isotopes: H-1, B-10, Li-6 which are involved in many relevant processes (batteries, fuel cells, combustion, fuel injection, energy storage, and two-phase flow, plant growing, wetting) and the study of porous media on different length scales and structures. On the other hand, heavy elements get well transparent, in particular U, Pb, Bi, Ta, Au, Pt, Ag where is no reasonable way of the inspection of thicker layers given with X-rays (see Fig. 3).

Another important feature of neutron imaging compared to the X-ray options is the lower effect of beam hardening in the case of thicker material layers since spectral response of the detector is much less energy sensitive. This enables a much better tomography reconstruction for thicker samples.

5. Applications

The user profile at the neutron imaging facilities at PSI can be divided into three categories:

A: scientific users via the user access program [6], where the scientific value and the feasibility is evaluated and ranked by an external, international committee. The success rate is on the order of 30% - 50%, depending on the facility.

B: industrial users, mainly paying for beam time, data analysis and reporting. These studies are often kept confidentially and will not be published.
method development for PhD projects and dedicated applications according to new requirements of specific users.

Fig. 4: Examples of studies with neutron imaging methods, without any claim for completeness: this overview picture intends to demonstrate the diverse applications ranges and the obtained image data quality on the different length scale. Detailed information have to be found in the related literature or on the homepage: https://www.psi.ch/niag/

Fig. 4 gives a symbolic overview about the application range of the neutron imaging techniques. This is by far not complete and is still extending because the methods of neutron imaging are further improved.

The methods summarized in Fig. 2 and the topics indicated in Fig. 4 (as examples only) deliver the intersection set for individual real application with the choice of the most suitable investigation methods. There is a high flexibility needed to come to this optimum with respect to the neutron spectrum, FOV vs. sample size, acquisition time and image quality. Since the variety of applications is very high it is hard to highlight individual ones most. Neutron imaging is a universal technique now like X-ray imaging (with its dominance in the medical field). Fields like electro-chemistry, porous media studies on the macro-scale, plant behavior in soil, nuclear fuel and cladding, two-phase phenomena (as hydrogen storage) and archaeometry are very promising and are already successfully.

From the studies at the PSI facilities we want to highlight in this report the following application cases which are representative for similar studies in other labs. They also sketch the trends in science and technology with the request for the application of advanced neutron imaging techniques.

Li-ion batteries this kind of supplier of electricity are already common but have potential for further performance improvements (capacity, charging speed, reduced aging behavior, …). For this purpose, several analysis techniques are required to understand the battery properties under operation. Next to the common neutron diffraction investigations, neutron tomography has a promising performance since the contrast for Li-6 is huge and migration of Li ions can be investigated in time and space with high quantitative accuracy. Fig. 5 compares slices from a tomography data set with a small Li-ion battery, obtained with cold neutrons and X-ray. These data are very complementary and underline the high visibility of Li in the neutron case.

Corrosion of metals, in particular of iron, is a damaging process of high economical relevance. Neutron imaging measurements can contribute to the understanding of the corrosion processes, in particular in hidden structures. This is caused by the high penetrability through metals and the high contrast to the corrosion products containing hydrogen and oxygen. The example in Fig. 6 of a heavily corroded nail from the Roman period (2000 years ago) compares the neutron and X-ray tomography data where the visibility of the corrosion layer is well pronounced in the neutron data while the X-ray slice describes more the metal distribution. The intensive analysis of these data is described in [8].
Fig. 5: Tomography slices of a Li-ion battery with X-rays (left), showing the metallic structure, and cold neutrons (right), indicating the Li distribution [7]; the length of the cell is about 25 mm only.

Fig. 6: Tomography study of a corroded nail from the Roman period: left – cold neutron imaging data; right – data of X-ray measurements [8], indicating the high sensitivity of neutrons for the detection of corrosion products

Fig. 7: Injection process of a Diesel nozzle under 450 bar pressure within 2.5 ms, integration over 1500 cycles, 0.8 ms delay, FOV about 5cm*10 cm

**Fuel injection:** Diesel engines are in use not only in the public transportation systems (cars, busses) but in particular in trucks and ships. The combustion process is determined in massive manner by the fuel injection systems. The efficiency of the combustion triggers the fuel consumption and the amount and quality of the exhaust gases. Therefore, a high economic and environmental impact for the study of the fuel injection systems is given.
Both the fuel-vapor after leaving the nozzle and the erosion of the nozzle itself are the focus of studies with neutrons. These investigations can be performed either in high spatial resolution or high temporal resolution, mainly in stroboscopic mode since the injection is a repetitive process [9]. Even if this approach averages over many (identical) events, the characteristic behavior is highlighted in the resulting data.

**Magnetic domain wall distribution:** Neutrons are sensitive for magnetic fields and structures due to their inherent magnetic moment. This behavior can be used to understand the structure and the changes of magnetic domain wall distributions in bulk magnetic sheets. For this purpose, a specific neutron grating interferometer has to be applied [10] which is sensitive for the domain walls via the “dark field signal” [11]. The changes of the domain wall structures were successfully be investigated during the application of static and dynamic magnetic fields to the metallic sample of Goss oriented steel.

![Image](image1.png)

**Heavy metal transmission:** As mentioned above and illustrated by Fig. 3, many heavy elements and their isotopes can be penetrated by neutrons much better than by X-rays. This behavior has some consequences for applications, in particular for noble metals like gold, platinum or silver which cannot be studied in bulk by X-rays but with neutrons. The knowledge about porosity, elemental distribution in alloys and even material fakes can be observed easily by neutron radiography and tomography. An example of cultural historical relevance is given in Fig. 9, describing the investigation of the sculpture found near Avenches (Switzerland), attributed to Marcus Aurelius and made of pure gold (1.5 kg, 33 cm height). It was possible to perform a full set of neutron tomography studies

![Image](image2.png)
since the transparency for thermal neutrons is given. By means of modern tomography analysis tools, the material layer thickness was derived voxel-wise and valuable information was derived to understand the manufacturing process of this 2000 years old object [12].

6. Outlook

The further development of neutron imaging techniques and their application depends strongly on the access to useful neutron beams. There is unfortunately the trend to shutdown aged reactor facilities (Berlin/D, Saclay/F) in the next few years, but some new reactors are under construction (Argentina, Jordan, Russia) with the clear aim to include neutron imaging facilities from the beginning. On the other side, even smaller sources can now do neutron imaging due to the high detector efficiency. Upcoming projects with accelerator driven sources should take into account the imaging capabilities on the current state-of-the-art. Due to the high sensitivity of the new digital detection systems reasonable results can be obtained even at very low intensities within minutes and hours. It depends on the particular site of the source which investigations and applications are most useful (for training, lectures on neutron physics, particular practical purposes). Because the neutron source is often available as “starter kit”, more effort for a useful detection system has to be spent. The advices of experienced facility operators are certainly useful.

Since the potential for neutron imaging applications is by far not exploited, more advertisement to the different research fields and to industry is needed to establish further connections and applications. An international platform, e.g. via ISNR, might help to network the facilities better and to exchange customers and know-how.

References

[1] O. Peter, Neutronen-Durchleuchtung, Z. Naturforsch. 1, 557–559 [1946]
[2] P. Tritic, J. Hovind, C. Grünzweig, A. Bollhalder, V. Thominet, C. David, A. Kaestner, E. H. Lehmann, Improving the Spatial Resolution of Neutron Imaging at Paul Scherrer Institut – The Neutron Microscope Project, Physics Procedia, Volume 69, 2015, Pages 169-176, doi:10.1016/j.phpro.2015.07.024
[3] N. Kardjilov, I. Manke, A. Hilger, S. Williams, M. Strobl, R. Woracek, M. Boin, E. Lehmann, D. Penumadu, J. Banhart (2012). Neutron Bragg-edge mapping of weld seams. International Journal of Materials Research: Vol. 103, No. 2, pp. 151-154.
[4] C. Grünzweig, Neutron grating interferometry for imaging magnetic structures in bulk ferromagnetic materials. Dissertation ETH Zurich (2009), http://dx.doi.org/10.3929/ethz-a-005901094
[5] S. Peertmans, A. King, W. Ludwig, P. Reischig, E. H. Lehmann, Cold neutron diffraction contrast tomography of polycrystalline material, Analyst, 2014, 139, 5765-5771, DOI: 10.1039/C4AN01490A
[6] https://duo.psi.ch/duo/
[7] C. Grünzweig et al., Study of Li-ion batteries with neutron imaging, submitted
[8] C. Gervais et al., Assessing dechlorination treatment with combined Neutron and X-ray tomography, submitted
[9] S. Jollet Experimentelle und numerische Untersuchungen der instationären dynamischen Innenströmung in Dieselinjektoren (Leibniz Universität Hannover: Dissertation 2014)
[10] C. Grünzweig, Dissertation ETH Zurich Nr. 18612, 2009
[11] B. Betz et al., Magnetization Response of the Bulk and Supplementary Magnetic Domain Structure in Hig-Peoumiaility Steel Laminations Visualized in Situ by Neutron Dark-Field Imaging, Physical Review Applied 6, 024023 (2016)
[12] A. Pury-Gysel, E.H. Lehmann, A. Giunila-Mair, The gold bust of the Roman Emperor Marcus Aurelius from Aventicum, Journal of Roman Archaeology, Volume 29 (2016), p. 478-486