<table>
<tr><td>ESRF</td><td>Experiment title:
Imaging fast processes in metal foams and thixo-alloys by in situ high speed microradiography</td><td>Experiment number:
MA-485</td></tr>
<tr><td>Beamline:
ID15a</td><td>Date of experiment:
from: 9th July 2008 to: 12th July 2008</td><td rowspan="2">Date of report:
8 Dec 2008
Received at ESRF:</td></tr>
<tr><td>Shifts:
12</td><td>Local contact(s):
M. Peele</td></tr>
<tr><td colspan="3">Names and affiliations of applicants (* indicates experimentalists):
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</table>

Report:

In a previous experiment we proved that by combining fast CMOS cameras with dedicated indirect pixel detector optics it is possible to increase image acquistion speed up to several thousand frames per second (FPS). The required high photon flux density is available when using the white beam of a third generation light source's insertion device. Our first experiments at ID19 (ME 1237) allowed us to image cell wall collapse in a liquid metal foam *in situ* at a frame rate of 4 000 FPS (equals to 250 µs time sampling).

In this experiment we aimed at

1. Projection image sequences containing spatial 2d information (µm range) about the foam structures and semi-solid alloy structures and its temporal evolution (down to <<1 ms time resolution). Recent improvements in our fast imaging instrumentation and the use of the ID15a beamline will yield sequence rates up to several 1 000 FPS with high signal-to-noise ratio.
2. Temperature information of the sample and furnace for each radiographic image.
3. 2d image analysis yields quantitative information about the coalescence rates, drainages, velocity fields and specially foam expansion in directions perpendicular to the beam direction.

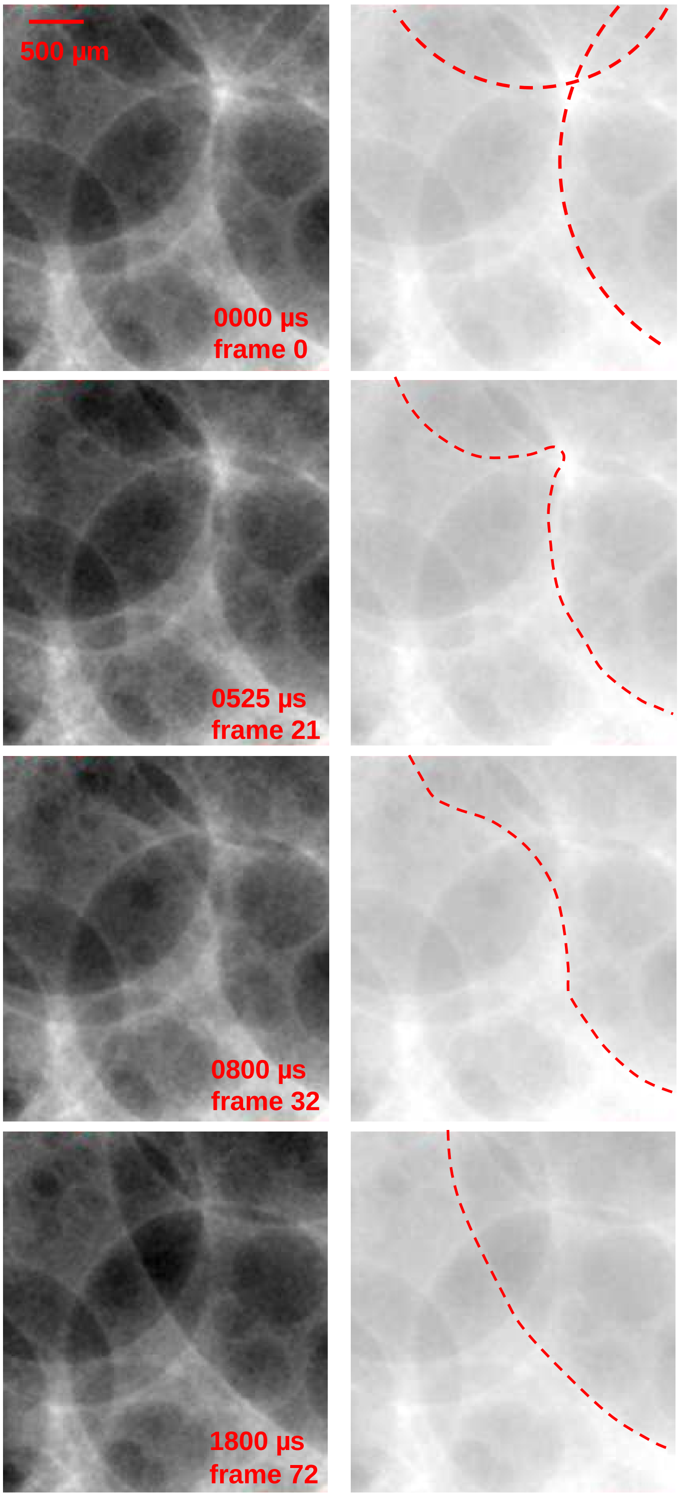

Figure 1: Left column: image sequence taken out of a series of 184 000 which shows the merging of two pores (25 µs exposure time / 40 000 FPS, 20 µm effective pixel size); right column: sketch highlighting major features [2].

Experiments were carried out at the beamline ID15a [5]. The corresponding white beam mode was chosen (filtered with Cu and/or Si attenuators) in order to reach a photon flux density high enough to perform micro-radioscopy.

A suitable X-ray pixel detector for our applications should combine high spatial resolution, high detection efficiency and high acquisition speed. Hybrid pixel detectors or Charge-Coupled Device (CCD) cameras which are used in direct X-ray imaging are limited in terms of pixel size, radiation resistance and x-ray stopping power. Therefore we apply indirect pixel detectors which were first introduced in 1975 for live X-ray topography. During the 1990s the concept was developed further for synchrotron-based micro-imaging, allowing one to work with a spatial detector resolution up to submicrometer. Here, the luminescent image of a scintillator screen is projected via visible light optics onto the chip of a digital camera.

Special white beam optics have been developed by the ESRF in order to stand the high heat load of a white beam emitted by a third generation ring's insertion device [5]. We succeeded to acquire X-ray movies with up to 40 000 frames per second (FPS) using those in combination with a fast CMOS cameera. Bulk LuAG:Ce (Ce doped $Lu_3Al_5O_{12}$) and YAG:Ce (Ce doped $Y_3Al_5O_{12}$) are applied as scintillator screen [5].

For the ultra-fast digitalization of the scintillator's luminescent image as projected via the optical system we use the novel high-speed camera Photron Fastcam SA-1. The camera's CMOS chip uses 1024 x 1024 pixels, each 20 µm in size. The peak quantum efficiency is 42% at 640 nm, the dynamic range 10bit (800:1) using a 12bit digitalization. The minimum shutter time is 2 µs. A charge of 5.5 electrons in the potential well of the chip corresponds to one signal unit (ADU). Up to 5 400 full frames per second can be acquired,

up to 675 000 FPS when using a region of interest. For fast intermediate data storage a 32 GB onboard memory array is available which defines the maximum recording length.

As example images we show *in situ* X-ray radioscopy of metal foaming. First synchrotron-based *in situ* radiography with moderate frame rates around 1 FPS already showed the high potential of this approach in order to study pore coalescence and the corresponding stability of cell walls [4].

Foamable pre-cursor materials were produced using the powder-metallurgical route. *In situ* foaming was performed using a dedicated furnace design [3]. Using the intense white beam and running the Photron CMOS camera with a region of interest allowed us to record X-ray movies of the foaming process with 40 000 FPS (25 µs time sampling, 20 µm spatial sampling). With this spatio-temporal micro-resolution we were able to picture the collapse of a single cell wall including the relaxation of the novel pore. Selected frames of a time sequence consisting of 184 000 are displayed in Fig. 1 and 2 (left column: single frames, right column: major events sketched with the original image faded into the background). We were able to sample an event lasting around 2 ms with ca. 70 frames. For watching the full movie see [6].

Approx. 40 X-ray movies of *in situ* metal foaming and thixo-casting were taken. This huge amount of data (600GB) is currently processed. Further publications based on the results are foreseen.

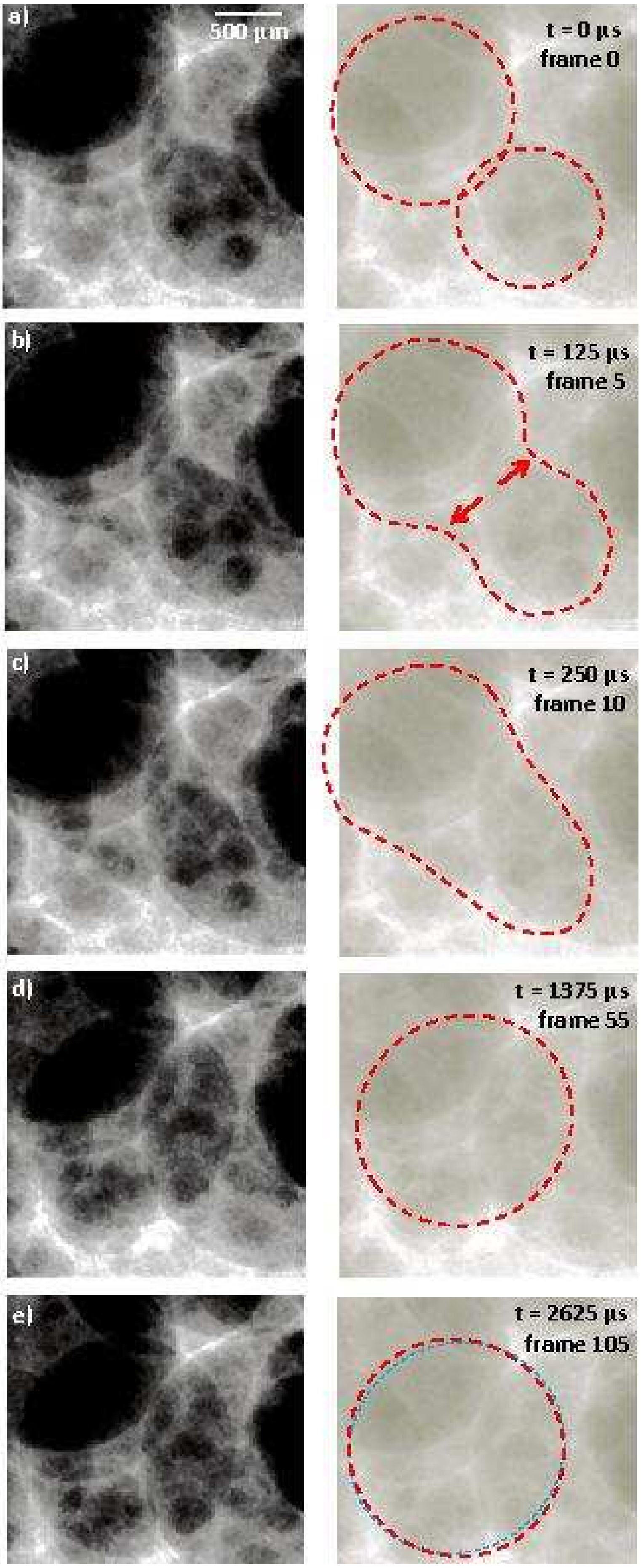

Figure 2: Left column: image sequence taken out of a series of 184 000 which shows the merging of two pores (25 µs exposure time / 40 000 FPS, 20 µm effective pixel size); right column: sketch highlighting major features [1].

References:

[1] A. Rack, F. García-Moreno, T. Baumbach, J. Banhart, "Synchrotron-based radioscopy employing spatio-temporal micro-resolution for studying fast phenomena in liquid metal foams", Journal of Synchrotron Radiation (submitted).
Abstract– Investigations of pore coalescence and individual cell wall collapse in an expanding liquid metal foam by means of X-ray radioscopy with spatio-temporal micro-resolution are reported. By using white synchrotron radiation for imaging, the rupture of a film and the subsequent merger of two neighboring bubbles could be recorded with a time sampling of 40000 frames/s (25 µs} exposure time) and a spatial sampling of 20 µm. The rupture time of a cell wall was found to be in the range of 300 µs. This value is in agreement with theoretical considerations which assume an inertia-dominated rupture time of cell walls in liquid metal foams.

[2] A. Rack, F. García-Moreno, O. Betz, S. Zabler, C. Schmitt, T. dos Santos Rolo, A. Ershov, T. Rack, L. Helfen, J. Banhart, T. Baumbach, "Synchrotron-based radioscopy with spatio-temporal micro-resolution using hard X-rays ", Proc. of the IEEE NSS MIC 2008 Conference, Dresden, Germany (submitted)
Abstract–The use of highly intense synchrotron light sources allows the next step in the fast imaging development: the use of hard X-rays. Micro-radiography as an established method to image the internal structure of an object with micrometer resolution can be extended to study its temporal evolution as well. While direct converting pixel detectors are known which can acquire images with high frame rates here detectors are needed with higher spatial resolution which can stand the highly intense synchrotron photon flux. Our approach is based on indirect pixel detectors which are already known for micro-imaging at synchrotron light sources. We combine those with CMOS cameras in order to achieve frame rates of up to 40 000 images per second, thus progressing to micro-radioscopy. Potential applications are studies of living insects with moderate frame rates up to 250 images per second (4 ms exposure time), velocity fields within a semi-solid alloy during a thixo-casting process and ruptures of individual cell walls in a liquid metal foam imaged with up to 40 000 frames per second (25 µs exposure time).

[3] F. García-Moreno, A. Rack, L. Helfen, T. Baumbach, S. Zabler, N. Babcsan, J. Banhart, T. Martin, C. Ponchut, M. Di Michel, "Fast processes in liquid metal foams investigated by high-speed synchrotron x-ray microradioscopy", Appl. Phys. Lett., vol. 92, no. 13, pp. 134104-1 - 134104-3, 2008.

[4] J. Banhart, H. Stanzick, L. Helfen, T. Baumbach, "Metal foam evolution studied by synchrotron radioscopy", Appl. Phys. Lett., vol. 78, no. 8, 1152–1154, February 2001.

[5] M. Di Michiel, J. M. Merino, D. Fernandez-Carreiras, T. Buslaps, V. Honkimäki, P. Falus, T. Martins, O. Svensson, “Fast microtomography using high energy synchrotron radiation”, Rev. Sci. Instrum., vol. 76, pp. 043702-1 – 043702-7, 2005.

[6] http://www.alexanderrack.eu/ieee_movie.avi - last visit November 2008.