Use of X-Ray Radiography to Characterize the Structure of Expanded Polystyrene Foam

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Introduction

The Lost Foam Casting (LFC) Process is a relatively new technology that is now experiencing widespread use in industrial applications. An Expanded Polystyrene (EPS) foam pattern is coated with a refractory coating and surrounded by sand. When molten metal is poured into the pattern, the foam degrades and passes through the remaining foam, coating, and into the sand.

In order to model and control the LFC process it is necessary to characterize the structure of LFC patterns. Historically, this has been done using macroscopic measures of foam density and "fusion". Fusion has been quantified by use of a measure of connected void fraction. In this measurement, olive oil is allowed to soak into a sample of foam. By measuring the dry mass, the soaked mass, and the volume of the sample, it is possible to compute the percent of connected void space as a fraction of total sample volume.

Industrial Analytics Corporation has performed proof-of-concept experiments that allow local measures of foam density and connected void space using x-ray radiography. A custom designed x-ray system is used to image EPS foam, both dry and soaked in olive oil. This provides 2D representations of the local density structure of foam and information related to intra-bead void fraction and inter-bead macro porosity. This paper provides an overview of both the experimental conditions used to acquire the images, and the insights that were gained into the problem of EPS foam characterization.

Experimental Setup

The custom-designed x-ray system for measuring the 2D local density structure of the EPS foam is shown in the picture on the right. In the foreground is an Oxford Instruments Model XYTF x-ray source. This source is designed for the 10 to 50 kVp energy range and delivers up to 1 mA source current. A 60 micron focal spot size allows modest magnification ratios without blurring of the image.

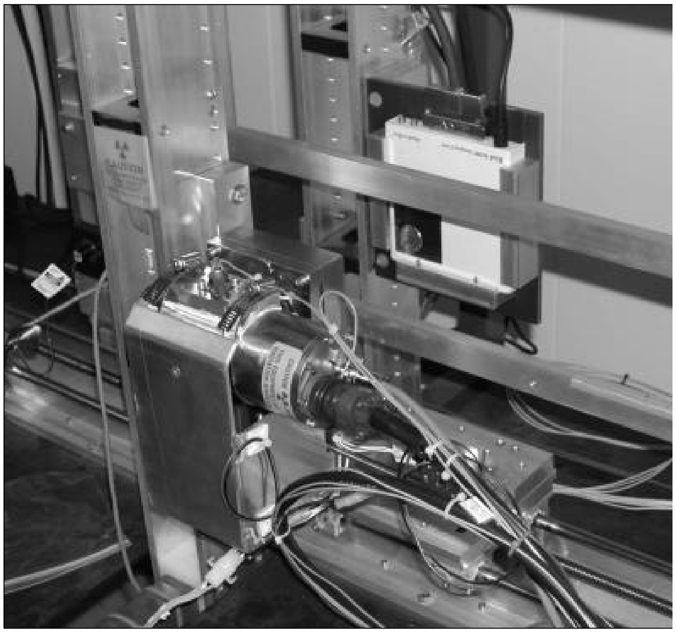

Figure 1 – X-ray system for foam characterization.

To the right of the source in figure 1, mounted behind the movable gantry, is a Shad-o-Box 1024 digital x-ray camera made by Rad-icon Imaging Corp. The camera features a 1024 by 1024 pixel CMOS photodiode detector with 10 lp/mm resolution (the black square facing the x-ray source, with the quarter set inside it, outlines the actual imaging area). The photodiode array is mounted in close contact with a GdOS scintillator screen that converts the incoming x-rays to visible light. The camera typically runs at anywhere from a few hundred milliseconds to several seconds of exposure time, and several images can be averaged together to reduce the x-ray shot noise.

The custom-built gantry system is under full computer control, as are the x-ray source and the camera. The sample stage allows for both horizontal and vertical movements of the sample. Samples up to 10 by 40 inches can be scanned in an automated sequence. A second generation test system (not shown) also includes a rotational stage that can be used to acquire data sets for computed tomography (CT) studies of various parts.

The typical imaging conditions that were used to study the foam samples are 15 kVp and 800 µA, with a frame exposure time of four seconds. A geometric magnification factor of 1.5 was used to obtain images, and ten frames were typically averaged together to reduce the photon shot noise in the images. Images are also routinely corrected on a pixel-by-pixel basis for camera gain and offset, as well as for variations in the uniformity of the x-ray beam. The Shad-o-Box camera digitizes the images to a resolution of 12 bits, and it can resolve spatial details in the image as small as 50 µm.

Foam Structure

Figures 2 and 3 show two examples of x-ray images of EPS foam pieces. When preexpanded EPS beads are blown into a mold and fused with steam they deform into a complex three-dimensional structure. Adjacent beads expand and their surfaces deform into flat planes of denser material. When those flat planes are parallel to the x-ray beam, they form dark lines on the image. The amount of fusion between adjacent cells can be controlled by the steam time. As steam time is increased, bead expansion increases, creating larger planes with greater length and definition (see Figure 3).

A commonly used method to measure the amount of bead fusion in a foam sample is to soak the sample in olive oil. The oil is allowed to soak into the remaining interstitial spaces between the beads. The weight-to-volume ratios of the dry and soaked samples allow the calculation of connected void fraction in the sample.

X-ray imaging is also used to help visualize this process. Figures 4 and 5 show images of the same EPS foam sample before and after soaking in oil. The oil, being denser than the foam, provides much higher x-ray contrast than the foam beads alone. The same bead joint structures can be seen in both images, but after oil immersion, they are much harder to observe among the denser oil accumulations. Figure 4 shows that the oil tends to accumulate in large compact volumes. This means that most of the connected void space consists of large caverns connected by narrow arteries along partially fused bead surfaces.

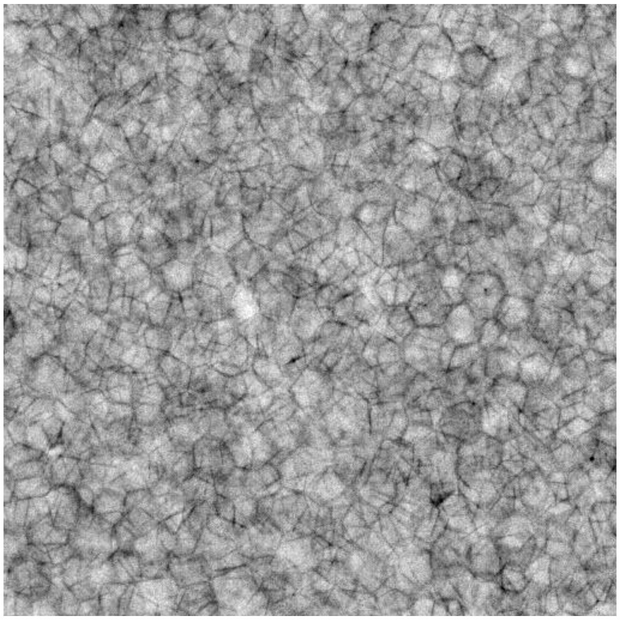

Figure 2 – X-ray image of low fusion foam sample.

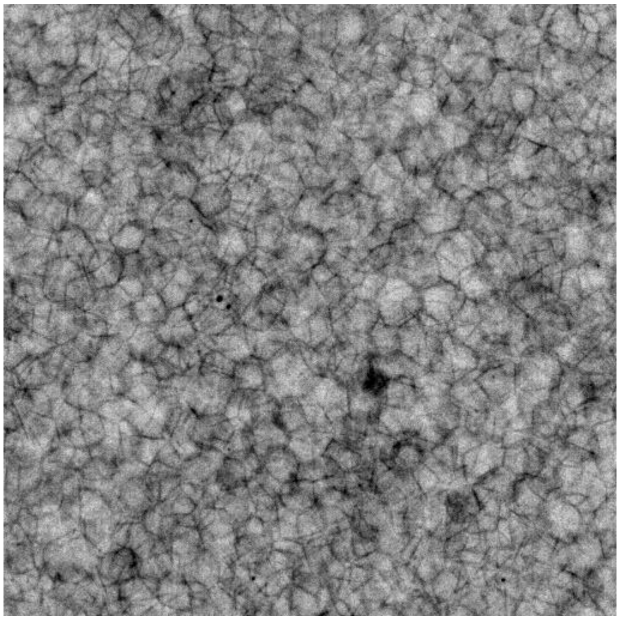

Figure 3 – X-ray image of high fusion foam sample.

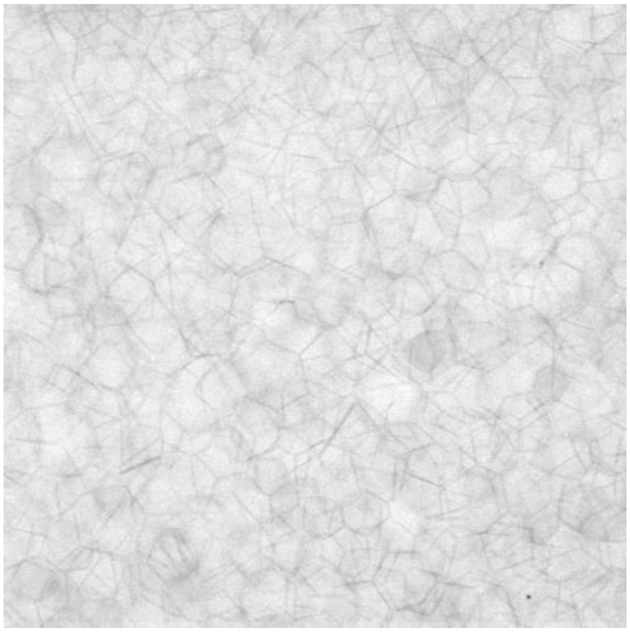

Figure 3 – Foam before oil immersion.

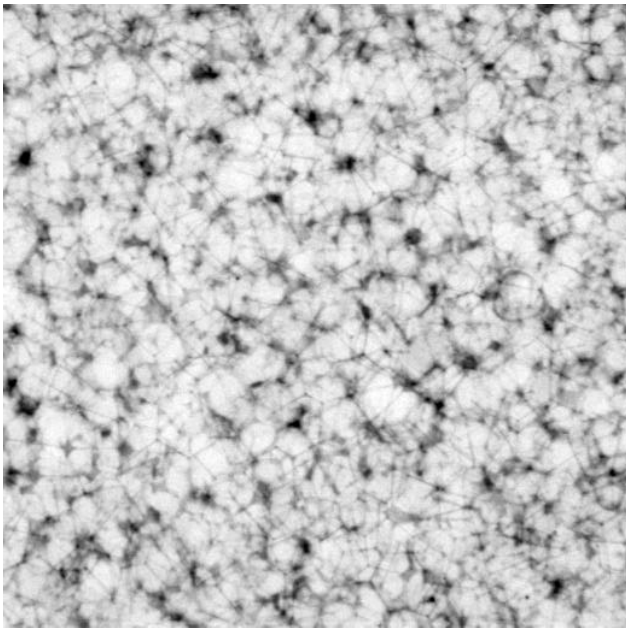

Figure 4 – Same foam sample after oil immersion.

Density Measurements

In a new experimental technique, the x-ray images themselves have been used to measure foam density on a pixel-by-pixel basis. This experiment requires the calibration of every pixel by obtaining a look-up table of mass per unit area vs. pixel reading (see Figure 5). The system response is calibrated by measuring a number of layers of polyethylene film under the same conditions as the EPS foam sample. The mass attenuation curves of polyethylene and polystyrene are nearly identical, and the mass per unit area of the polyethylene film samples is easily measured. The mass per unit area of the EPS foam along the x-ray path seen by a particular pixel can thus be read off the calibration curve. The density along the same path can be obtained simply by dividing the result by the thickness of the foam sample. In practice, this is all done in software.

The elegant simplicity of this technique stems from the fact that the calibration automatically compensates for complicated factors such as the polychromaticity of the x-ray source and the response non-linearities in the detector. Pixel-to-pixel variations in response, as well as angle effects due to the large active area of the detector, are automatically taken into account by performing the calibration for each individual pixel. An equivalent mass attenuation coefficient (MAC) of 2.6 cm^2/g is obtained from the measurements. This corresponds to the actual MAC of polyethylene at 9 keV, confirming that the density measurements are in the correct range. The average foam density obtained for the sample plate was 0.026 g/cm^3, with a standard deviation of 0.004 g/cm^3. Most of this variation is due to the measured differences in EPS foam density.

Conclusion

Density variations in EPS foam can have a detrimental effect on casting quality. We have shown that digital x-ray radiography can be used as a tool to characterize this important industrial process. X-ray images can be used to give qualitative feedback on foam density and connected void fraction. With the proper calibration technique, these same images can also be used to obtain quantitative density measurements. A custom-built imaging system with full computer control of the x-ray source, the camera and the sample stage is essential to carry out these experiments.

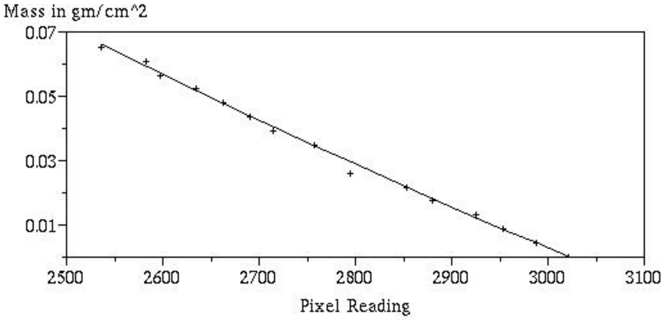

Figure 5 – Calibration curve for pixel (10,10).