A fast and non-destructive alternative to the burnout method for paperboard quality inspections using phase-contrast X-ray imaging

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ABSTRACT: An X-ray based quality inspection method for paperboard was implemented and tested as a fast and non-destructive alternative to the burnout method. An argument against X-ray imaging for inspection of paper and paperboard has been that X-ray absorption is low in paper. To overcome this limitation, we used phase-contrast X-ray imaging (PCXI), which gives higher contrast than conventional attenuation-based imaging for low-absorbing materials such as paper. The suggested PCXI method was applied to previously prepared and quality rated samples using the burnout method.

A strong similarity between the burnout images and the PCXI images was observed. In conclusion, further development of the phase-contrast X-ray method would provide an interesting option for replacing or complementing the standard burnout method.

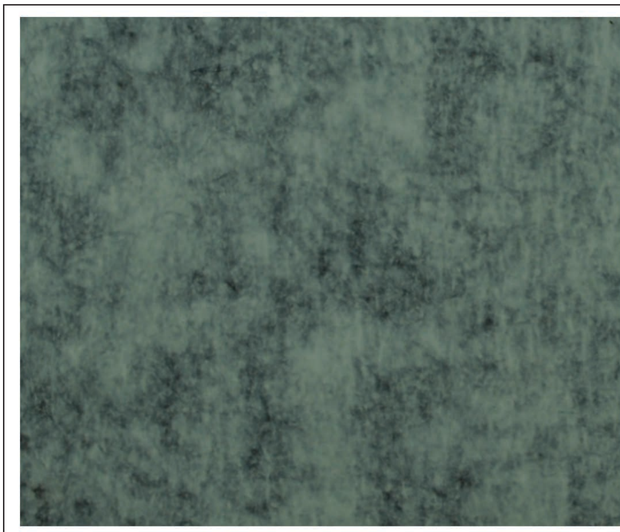
Application: Phase-contrast X-ray imaging could be directly applied on paperboard to produce "burnout-like" images, skipping the burning procedure.

Usually, a paperboard sheet contains a core of cellulose fibers that are coated on one or both sides with layers of calcium carbonate or kaolin [1]. One characteristic of a high-quality paperboard is the consistency in the expected ratio of the thickness of the core and the coating layers, across the whole sheet. The burnout method [2,3] is regularly used to monitor this consistency.

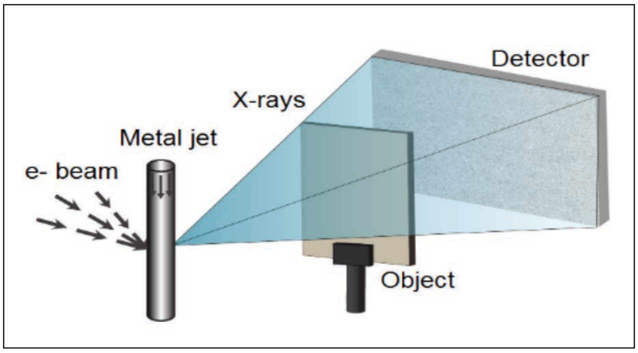
In the burnout test method, a paperboard sample is treated with an ammonium chloride (NH_4Cl) test solution (25 g/L NH_4Cl in a 50/50 volume mixture of 2-Propanol/water), and then placed under a heat gun or in an oven for 2 min ("burnout"). The burnt sample (**Fig. 1**) is then examined for color changes. The intention is to carbonize any exposed cellulose fibers and by doing so, produce contrast between the layers. Areas with a thicker or denser cellulose layer, and hence thinner or less dense coating layer, appear darker in the burnt sample.

The burnt sample is then either observed by a human observer (most likely in industrial monitoring) or analyzed by computer imaging software (more likely in research applications). Based on the texture of the burnt sample, a quality index is produced and assigned to the sample. This index is called burnout index and is a widely used standard.

The burnout method is a destructive process and the samples cannot be processed back to their original state. The process lacks repeatability and can be affected by many factors, such as temperature, chemical concentrations, and NH_4Cl solution distribution over the sample surface. The burnout method can be applied only to certain types of paperboards [4]. Considering these limitations, a non-destructive method, such as X-ray imaging, could help the industry perform quality inspection without destroying the samples. Furthermore, X-ray imaging is fast and repeatable. It would, in an ideal future scenario, be possible to take the whole production under observation. This



1. Photo of burnt paperboard.



2. Illustration of experimental setup.

would require an automated system, including final computer analysis of the collected data.

X-rays have been used widely in medical imaging and in various industries for their ability to penetrate materials, allowing non-destructive examination of inner structures. When X-rays pass through an object, they are attenuated, but also refracted and diffracted. In low-absorbing materials such as paperboard, the difference in attenuation between different parts is small, and hence the contrast in the resulting image is low. Phase-contrast X-ray imaging additionally uses the refraction and/or diffraction to create contrast. Several phase-contrast X-ray techniques exist, most noticeably the propagation-based [5], the grating-based [6], and more recently the speckle-based [7]. One main advantage of the phase-contrast methods is that for low-absorbing materials, you can get higher contrast at a limited dose or exposure time [8,9,10]. A previous paperboard study used the grating-based method to demonstrate a correlation between the burnout index and the so-called darkfield signal [10,11]. However, this study showed no images, and hence one could not really judge the similarity of the results. The spatial resolution was not high enough to reveal any actual paperboard structure, both due to the inherent low resolution of the dark-field image and to the equipment used (X-ray source with a focal spot size of 200 µm and an X-ray imaging sensor with 127 µm pixel pitch). The present study uses the propagation-based method, which is the simplest and most stable experimental arrangement and also the most advantageous for high-resolution imaging [8,9]. The equipment, further described in the Methods section, is chosen for high resolution (X-ray source with a focal spot size of 7.5 µm and an X-ray imaging sensor with 9 µm pixel pitch). The propagation-based phase-contrast method takes advantage of the free space between the object and the detector, which allows the wavefront distortion introduced by the object to propagate and develop into intensity differences [5]. The image registered by the detector will be a combination of the attenuation and phase signals. The phase contribution mainly shows up as characteristic edge enhancements at interfaces between different materials. To get a quantitative image of either the phase or the attenuation signal, a numerical process known as phase-retrieval [12] must be performed. In the Results section, several such images of paperboards, revealing details of their structures, are presented.

METHOD

The experimental arrangement of this study is illustrated in **Fig. 2**. The main difference compared to X-ray attenuation imaging is the longer distance between the object and the detector. Also, it requires a source of smaller spot size than a normal X-ray tube, as well as a high-resolution detector. The distances are flexible and can be adjusted based on the need for magnification, exposure time, and phase-contrast edge enhancement.

Phase-retrieval is applied to the edge-enhanced signals to reconstruct the phase image of the object. There are different methods for this [12]. In this work, Paganin's method [13] has been used, which is based on the assumption that the object contains a single material. The cellulose inside the paperboards was targeted as phase-retrieval material using its refractive index at the corresponding photon energy, e.g., $\delta = 1.59 \times 10^{-6}$, $\beta = 1.18 \times 10^{-9}$ at 14 keV. Here, δ represents the refractive index decrement, and β represents the imaginary part of the complex refractive index $n = 1 - \delta + i\beta$, where i is the imaginary unit.

The source was a liquid-metal-jet X-ray source with a

Sample	1	2	3
Quality index*	5	4	2
Fiber orientation	Fibers along fabrication line	Fibers transverse fabrication line	Arbitrary direction
Figure	Fig. 3	Fig. 4	Fig. 5
SSIM between photo and X-ray image	0.88	0.89	0.86

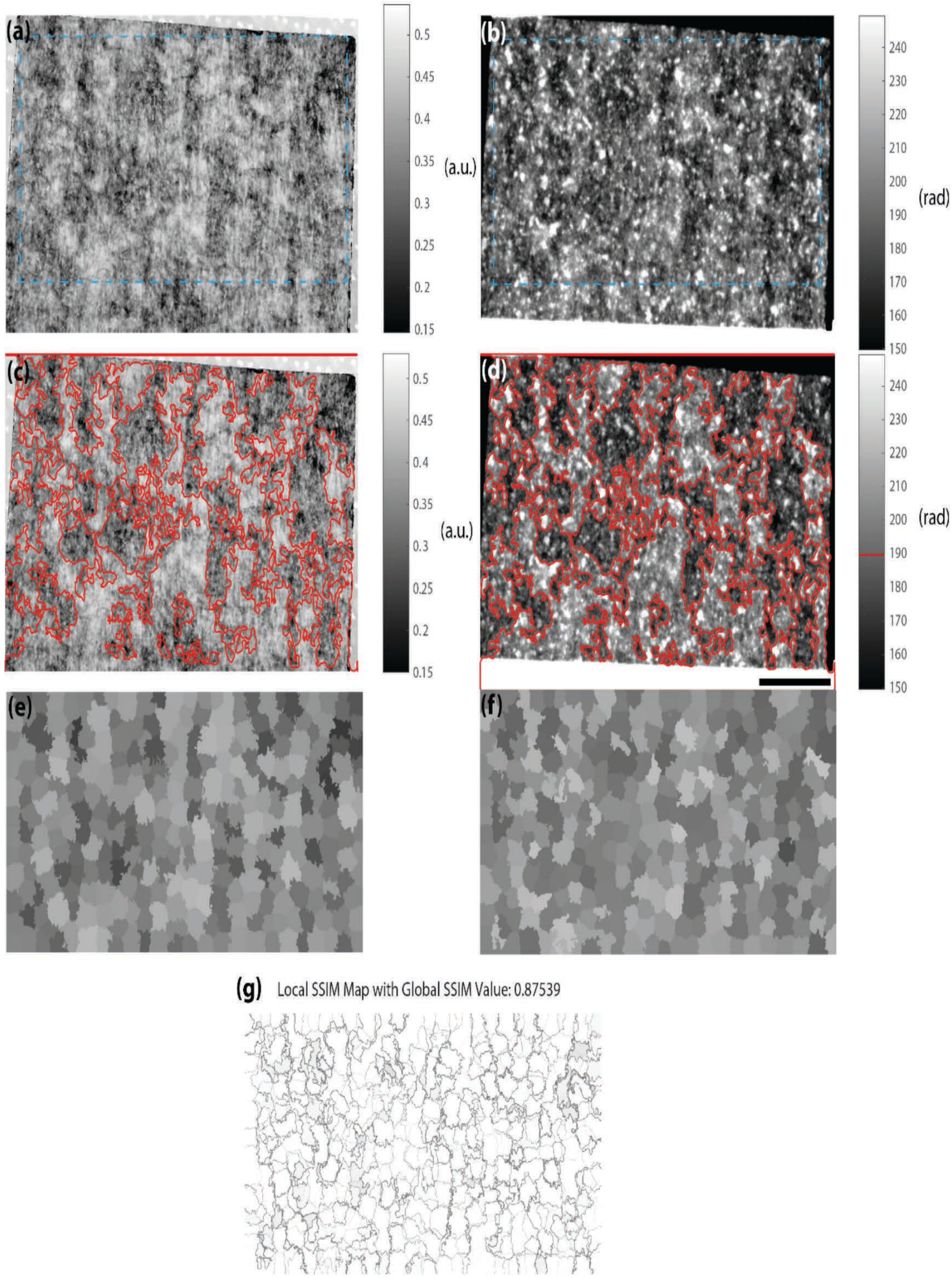
* Quality index runs from 1 (best) to 5 (worst).
SSIM = structural similarity index measure.

I. Three paperboard samples were studied.

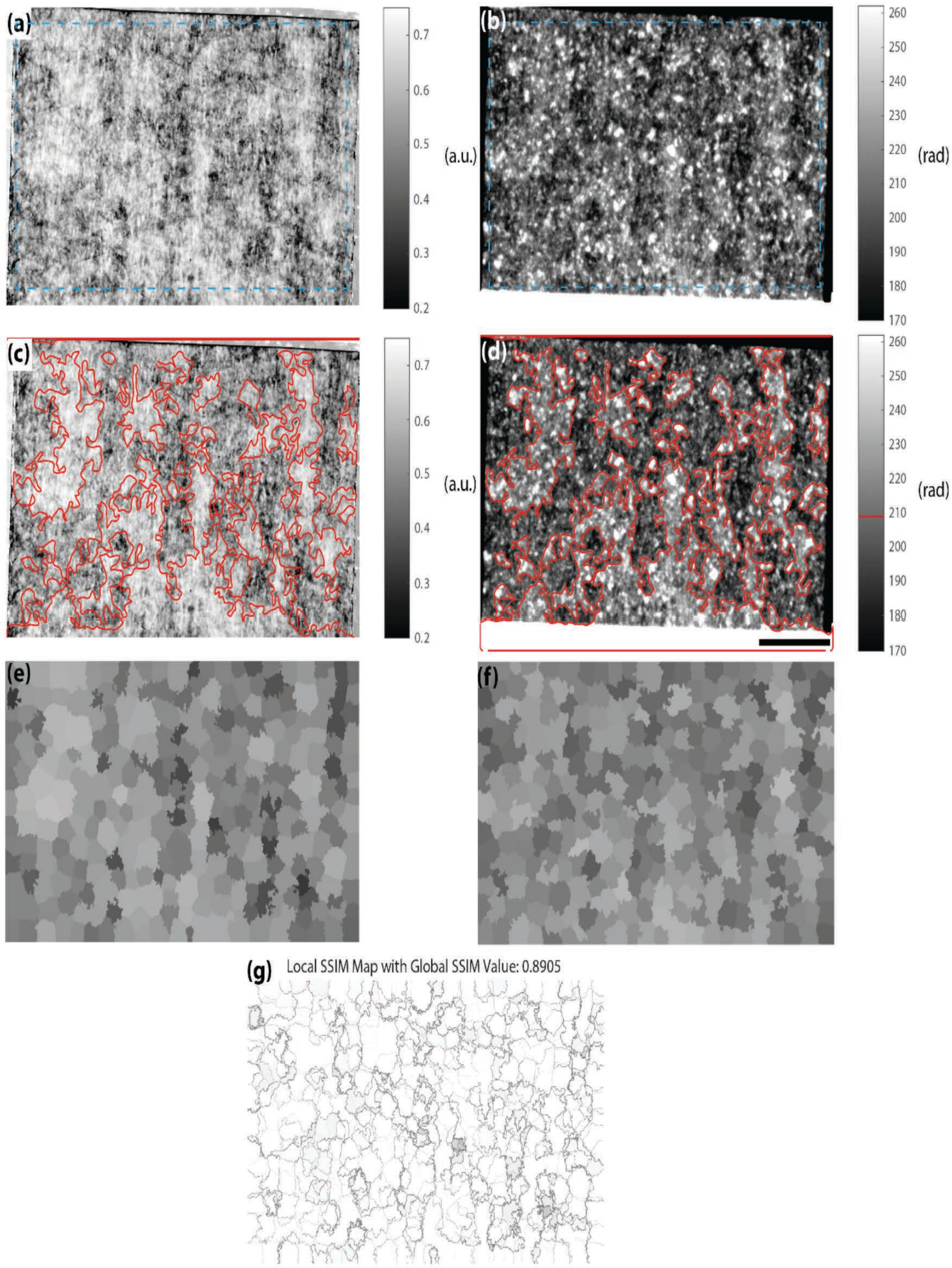
galinstan alloy as anode [14], as illustrated in Fig. 1. The X-ray source was operated at 50 kVp peak acceleration voltage and 0.6 mA tube current. The generated source spot size has an area contained within a full width at half maximum (FWHM) of 7.6 μm^2 x 7.5 μm^2. A charge coupled device (CCD) scintillator detector with a pixel pitch of 9 µm and FWHM of the point-spread function (PSF) of about 22 µm was used to record the images. The source-to-sample and source-to-detector distances were 0.55 m and 1 m, respectively.

RESULTS

The burned samples listed in **Table I** were studied using the X-ray setup, and their phase-retrieved images have been compared to their photos. Paperboards with three different quality indices were chosen. The quality index runs from



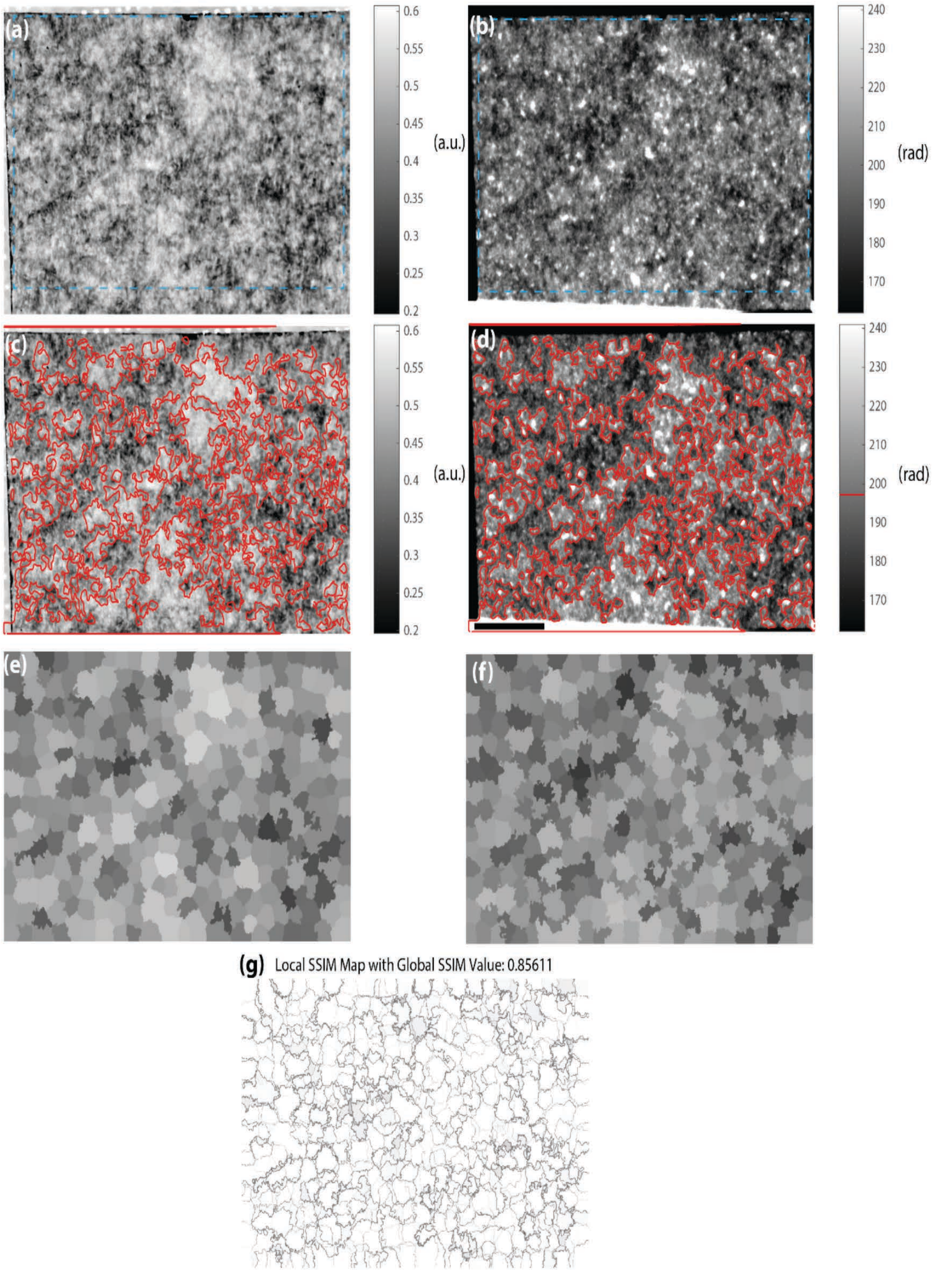
3. (a) Photo of sample 1, quality index 5. (b) Phase retrieved X-ray image of sample 1. (c) Photo of sample 1, with the contour lines from (d) superimposed on it. (d) Phase retrieved X-ray image of sample 1, with the contour lines generated from it based on the differences in phase shift. The threshold is visible in the scale bar in red. (e) Region of interest (ROI) of the photo, marked within cyan dashed lines in (a), binned to super pixels. (f) Binned X-ray image of ROI in (b). (g) Local structural similarity index measure (SSIM) map of (e,f).



4. (a) Photo of sample 2, quality index 4. (b) Phase retrieved X-ray image of sample 2. (c) Photo of sample 2, with the contour lines from (d) superimposed on it. (d) Phase retrieved X-ray image of sample 2, with the contour lines generated from it based on the differences in phase shift. The threshold is visible in the scale bar in red. (e) ROI of the photo, marked within cyan dashed lines in (a), binned to super pixels. (f) Binned X-ray image of ROI in (b). (g) Local SSIM map of (e,f).

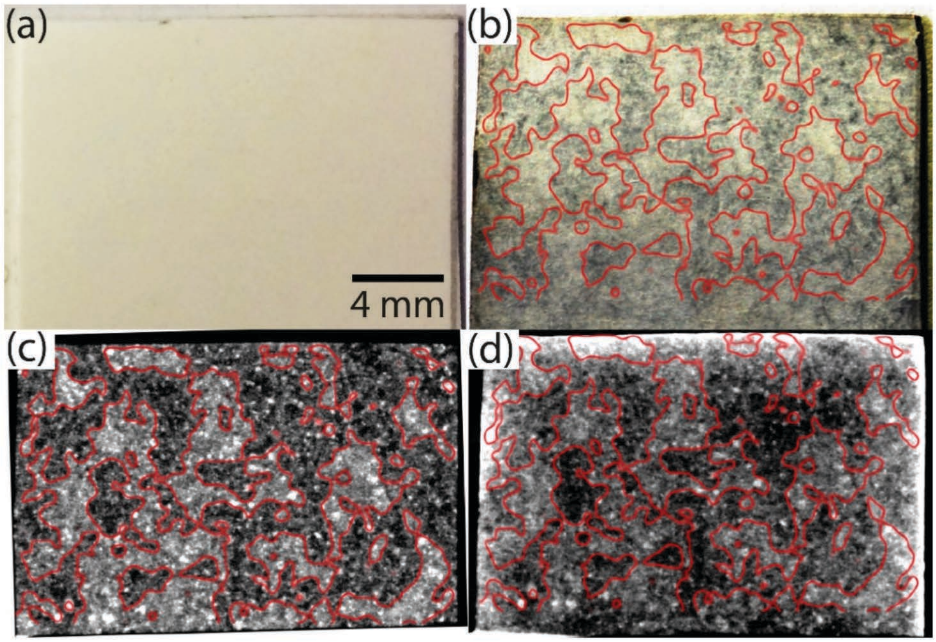
1 (best) to 5 (worst). The difference between a quality index of 4 and a quality index of 5 is, in the industry, likely to be the difference between keeping or throwing a batch away.

To illustrate the similarity between the suggested PCXI method and the burnout method, contour lines in the X-ray image and the burnout photo are compared. **Figures 3–5** show the three samples in the same manner: (a) contains a photo of the burned sample, and (b) contains a phase-contrast image of the same area. The (d) images in Figs. 3–5 are identical to the (b) images, except that contour lines are shown in red. The threshold of the contour line is marked in the scale bar on the right. The (c) images in Figs. 3–5 are identical to the (a) images, but they also contain the phase-contrast contour lines like the (d) images. This shows that the images match well. The (e) images and (f) images in Figs. 3–5 are the binned



5. (a) Photo of sample 3, quality index 2. (b) Phase retrieved X-ray image of sample 3. (c) Photo of sample 3, with the contour lines from (d) superimposed on it. (d) Phase retrieved X-ray image of sample 3, with the contour lines generated from it based on the differences in phase shift. The threshold is visible in the scale bar in red. (e) ROI of the photo, marked within cyan dashed lines in (a), binned to super pixels. (f) Binned X-ray image of ROI in (b). (g) Local SSIM map of (e,f).

images of the photo and of the X-ray image to 300 super pixels, respectively, using the *superpixels* function in MATLAB software from Mathworks (Natick, MA, USA). The purpose is only to demonstrate the larger features of the thickness variations. The structural similarity index measure (SSIM) [15] is calculated between the region of interests (ROIs) of the two binned images and shown in the respective (g) images. The ROIs are shown in cyan rectangles in (a, b) and are chosen to exclude the background and the metal clamp at the bottom of the X-ray images. The SSIM value indicates the similarity between two images. A value closer to 0 means low similarity, and there is high similarity if it is closer to 1. The SSIM values of the three samples are listed in Table I and have an average value of 0.87. The values can be further improved by better alignment of the photos to the X-ray images.



6. (a), (b): Photo of the paperboard sample before and after burning. (c), (d): Phase retrieved X-ray images of the unburnt and burnt sample. The contour lines were generated from (c) and then superimposed on (b) and (d).

One major difference between the phase-contrast and the burnout images is that the phase-contrast images contain small, bright, high-absorbing areas, making the phase-contrast images resemble a sky full of stars. This effect does not show up in the burnout images. It is likely due to the paper production method. Paperboards that do not meet the quality requirements are routinely ground into pulp and re-used in the cellulose layer of new paperboards. This means small parts of ground coating will also constitute part of the core. These fragments, inside the core as they are, will not affect the burnout method. However, they show up on the X-ray images as small, high-absorbing regions. This is the reason the SSIM is conducted between the binned images with super pixels—to keep the larger structures for comparison while excluding the influences of the bright pixels.

The previous finding that the phase-contrast signal correlates to the burnout index [10,11] has now been complemented with images. This indicates that the PCXI method is a possible alternative to the burnout method, returning similar visible information for expert inspection. The burnout method uses the reflectance of the surface to indicate the thickness variations in the coating. In comparison, the PCXI method is a more intuitive method to directly and quantitatively measure the phase shift, which is proportional to the thickness of the paperboard.

Verification of low burnout influence

As the phase-contrast measurements were performed on paperboard samples that had already been burnt, there is a risk that the burnout process affects the X-ray images, creating similarities that do not really exist. To eliminate this risk, we took X-ray images of one sample (from the same paperboard as sample 3, with quality index 2) both before and after burning. The results are presented in **Fig. 6**. The X-ray images are taken under the same conditions in both cases. It is evident that the patterns in the X-ray images of the unburnt and burnt sample (Figs. 6c and 6d) are similar. They also match with the patterns in the photo of the burnt sample (Fig. 6b). The phase-contrast image of the unburnt sample (Fig. 6c) was used to generate a contour line, which is then superimposed on the photo and the phase-contrast images of the burnt sample (Figs. 6b and 6d). There are brighter regions around the edges in the X-ray image of the burnt sample, as the edges were more exposed to the chemicals in the burnout process. In all, this shows that the X-ray image pattern is not significantly affected by the chemical treatment, and hence the conclusion that X-ray and burnout images give similar results was correct.

CONCLUSION

X-ray phase-contrast imaging was used on different paperboard samples, burnt and unburnt. A strong similarity was found between the phase-retrieved X-ray projection images and photos of burnt samples using the traditional burnout method. The results indicate that the method could be directly applied on paperboard to produce “burnout-like” images, skipping the burning procedure. The conclusion is that phase-contrast X-ray imaging has the potential to replace or complement the traditional burnout method to examine paperboard quality in the production line.

Although 40 s of exposure time was used in the PCXI measurements, the exposure time can be shortened to several seconds or less by adjusting the distances, by using a more powerful X-ray source, or by using a more efficient detector. This study revealed that the proposed method is of major interest in testing paperboard quality. Further work is required to properly evaluate the usefulness and the applicability of the method, by e.g., investigating more samples with all quality indices, by conducting a task-based analysis of the similarity, and establishing a method of generating quality indices from phase-contrast images. The last step might involve a high-spatial frequency filter to remove the influences of the coating fragments in the core. **TJ**

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ABOUT THE AUTHORS

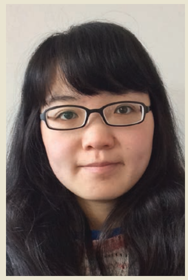
The pulp and paper industries are very important in Sweden. This research work has been conducted in collaboration with the Iggesund Holmen paperboard factory. This research will help Iggesund Holmen and other similar industries in fast and non-destructive quality testing.

Through our study, previous findings, where the phase-contrast signal correlates to the burn-out index [10,11], have now been complemented with images. The most difficult aspect of this research was that in low-absorbing materials such as paperboard, the difference in attenuation between different parts is small, and hence the contrast in the resulting image is low. Phase-contrast X-ray imaging (PCXI) adds the use of refraction and/or diffraction to create contrast.

We discovered that it is possible to use PCXI to image paperboards for application where conventional X-ray imaging is not as useful. Also, we found that those images can potentially be used to replace a method that is widely used by industries today. A particularly interesting finding was that a strong similarity exists between the phase-retrieved X-ray projection images and photos of burnt samples using the traditional burnout method.

For mills, PCXI has the potential to replace or complement the traditional burnout method to examine paperboard quality on the production line. Since it is possible to automate the process by using image processing/analysis tools, a future project could be to implement the proposed method on a production line for on-the-fly analysis and quality control.

Rezasson



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