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AUTOMATED CRACK DETECTION METHOD APPLIED TO CT IMAGES OF BAKED CARBON ANODE

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Abstract

Computed tomography (CT) is a powerful non-destructive technique providing a large amount of useful data to characterize carbon anodes. Previous works employed this technique to characterize baked anode samples and some relationships have been proposed for apparent density and total porosity as a function of X-ray attenuation coefficients. In this paper, an existing method of crack detection in 2D was applied on CT images of full-scale baked anode to estimate the amount of cracks. The crack detection method has however been modified to improve the termination procedure of the algorithm which was essentially based on the calculation of circularity of the percolated region. The improvement consists of calculating other percolated region properties in order to end adequately the percolation process. The proposed method has been applied to anode slices with and without stub holes.

Introduction

Carbon anode quality is a well-known concern of aluminium producers. On the one hand, they have to deal with changing raw materials properties. Cokes used to produce carbon anodes (shot coke, sponge coke, needle coke, etc.) are by-products of refineries and contains various impurities depending on the production process and supplier location. On the other hand, the aluminium producers must adjust the anode forming process parameters according to these changing raw material properties. The mixing, forming and baking processes are the main forming steps widely investigated over last decades in order to find a clear correlation between the final product and the raw material properties. A non-optimized forming process may yield anode defects which results in low quality anodes.

Anode cracking is a defect often encountered during the anode baking. Quantitative characterization of cracks within anode can be used as an indication of the global production process quality. Image processing is an efficient way to achieve this goal. Several image processing techniques are available for crack detection and have been summarized in literature [1]. Some focus on accuracy while others focus on decreasing computation time. On an industrial point of view, these techniques can be used to evaluate anode properties on a regular basis or after any changes in raw material or in the anode forming process.

Yamaguchi and Hashimoto [2] proposed a method based on percolation model, which was later improved by combining a low computation time and a good accuracy [1, 3]. The percolation method proposed by Yamaguchi et al. [3] is similar to a scalable window processing and takes into account the connectivity of percolated pixels. The method requires setting a local investigation window containing the focal pixel, or seed pixel. The seed pixel is then percolated and features of the percolated region are used to determine if the resulting cluster is a crack or not. To speed up the method, which was otherwise slower than conventional methods, Yamagachi et al. [3] introduced two processes preventing useless percolation. First, if the seed pixel is located in the background, i.e. not in a crack or in a pore, the percolation ends. The percolation also ends after reaching the boundaries of the local window if the circularity of the percolated region is higher than a given threshold. The crack detection method proposed by these authors has however some problems when pixel resolution decreases. This method will be discussed later.

In the present study, anode images have been obtained from X-ray computed tomography. The resolution is thus linearly proportional to object size, as discussed in literature [4, 5]. Cracks in anodes can be large; thus, the whole anode block must be scanned. The scanning of the whole anode leads obviously to low voxel resolution. Decreasing the resolution can thus decrease the contrast between void and carbon. In the present study, the width of typical crack is rarely higher than two pixels.

The result can be a region with several pixels having brightness close to the background one. It is thus necessary to prevent the inclusion of these pixels in the percolated region. As it will be discussed, circularity was not a sufficient parameter to stop the percolation and ultimately avoid flooding the local window. It was thus necessary to add a new restriction on the features of the regions at the end of the percolation process to filter those unwanted regions and to improve the crack detection method for this study.

X-Ray computed tomography data acquisition

Carbon anode images have been obtained by scanning a whole baked anode block using computed tomography (3D NDT imaging tool). This method has mainly one advantage that overcomes two disadvantages. The advantage is the nature of the technique itself, i.e. it is a non-destructive technique while measurement does not involve damaging or destruction of the sample and preserves crack integrity within the object. On the disadvantages side, the scanning area of the X-ray apparatus (Siemens Somatom Sensation 64) was designed for human body and consequently was too small for the anode (Figure 1). The block was thus sliced in 52 pieces of 2 inches thick as shown in Figure 2. Also, as discussed earlier, increasing the object size increases the voxel volume up to $0.7 \times 0.6 \times 0.7$ mm^3 (the thickness of voxels is 0.7 mm), and decreases the resolution. Therefore, contrast between cracks and background (carbon) is reduced.

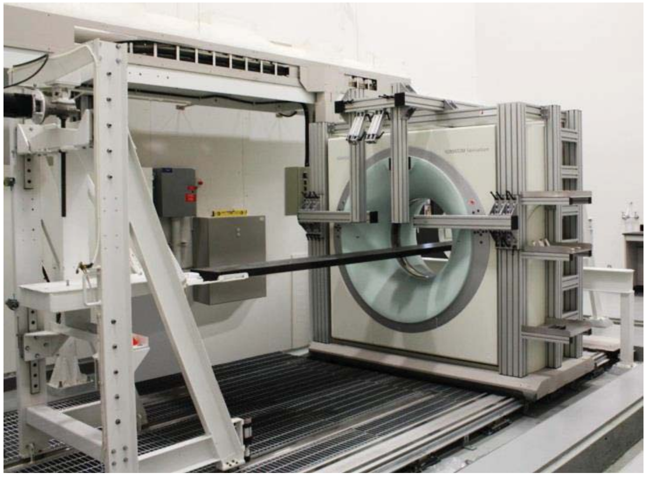

Figure 1 Siemens Somatom Sensation 64 located at INRS-ETE. Courtesy of INRS-ETE.

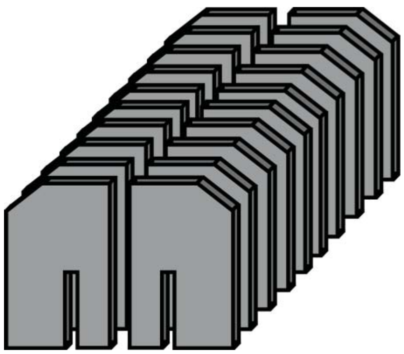

Figure 2 Scheme of anode slicing

The output of the tomography process must also be adapted to the percolation algorithm inputs, i.e. grayscale images. CT scan gives attenuation coefficient, which is linearly proportional to the density of carbon materials [4, 6] and thus can be converted directly in grayscale image without any loss of information.

To test the crack detection method, two samples were used and one image in each sample was extracted. The two samples were identified according to their distinctive geometrical features. Hence, the first slice is located near one of the ends of the anode (E position) and the second one contains a stub hole (SH position). The precise locations will not be divulgated. The crack detection method also requires 2D images. The two images, located in the middle of each 3D matrix of the attenuation coefficients, were thus used and shown in Figure 3.

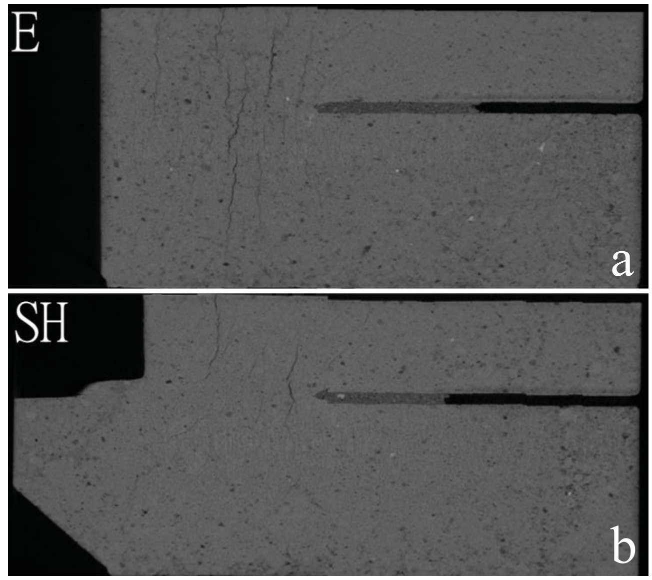

Figure 3 Anodes images used to test the crack detection method. a) Anode end (E location). b) With a stub hole (SH location).

Summary of the crack detection method

Percolation-based image processing algorithm

Percolation methods are effective to describe continuous regions such as voids and cracks. The physical features guiding the percolation also change according to the region of interest. For cracks, circularity is the main feature. As mentioned earlier, the algorithm used in this paper is given in detail in literature [3] and the flowchart is illustrated in Figure 4. The algorithm has been implemented with Matlab®. The most important parameters of this method are the seed pixels p_s, the initial window size N, the maximum window size M, the brightness threshold T, the acceleration parameter w, the circularity F_c, and the circularity threshold T_s. The threshold T is updated at each step of the percolation as following:

$$T = \max\left(\max_{p \in D_p}\left(I(p)\right), T\right) + w \quad (1)$$

where $I(p)$ is the brightness of the pixel p. The parameters N, M and the threshold must be determined prior to the percolation process (pre-processing) while the circularity, or roundness, is a geometric property measuring how close the percolated region is to a circle. This parameter can be defined as follows:

$$F_c = \frac{4\pi \cdot A}{P^2} \quad (2)$$

where A is the area of the percolated region, or the number of pixels in it, and P is the perimeter of the region. The circularity of long thin crack tends toward 0. As other image processing tools, all parameters are defined considering grayscale images, i.e. pixel values ranging from 0 (black) to 1 (white). Finally, the percolation process must be carried out for each seed pixel.

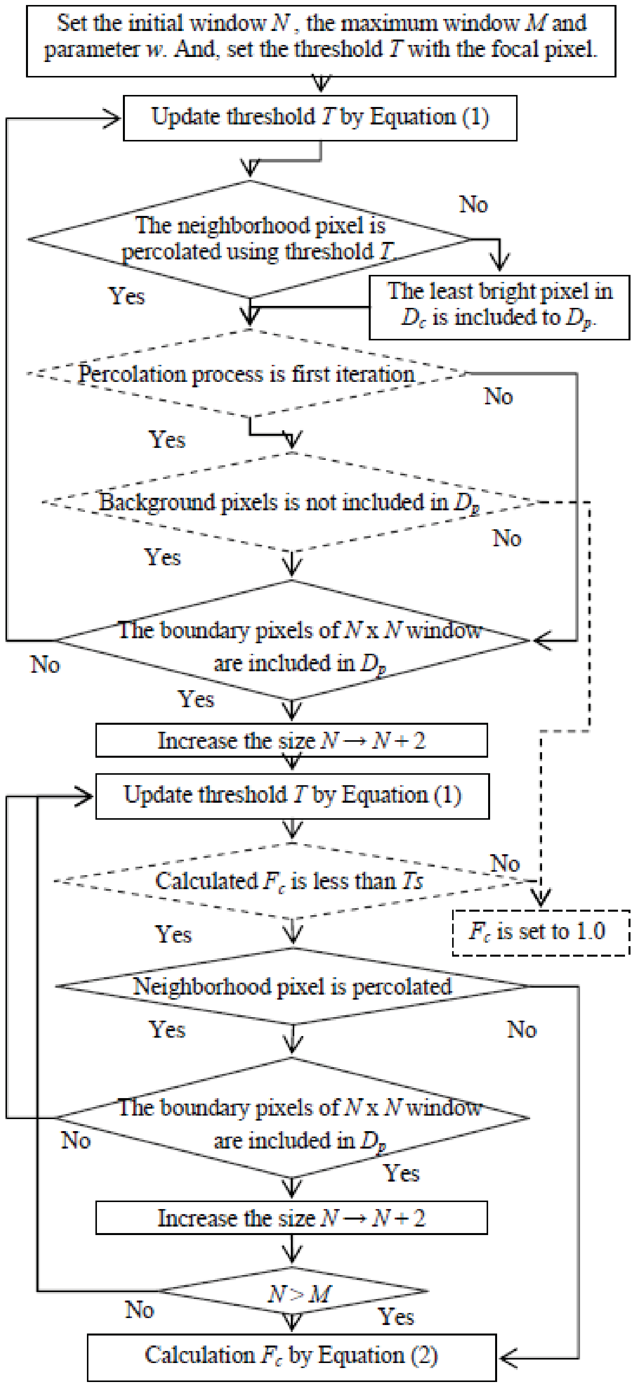

Figure 4 Flowchart of the percolation method [3].

Seed pixels detection

Due to the size of the anode block images, it is necessary to provide automated seed pixel detection. It is not practical to choose manually the seed pixel for each crack. A good seed pixel detection method needs to be fast but not necessarily very precise. The percolation algorithm will verify if each seed pixel is really part of a crack.

In the spatial domain, cracks appear as discontinuities in the image. These discontinuities introduce high frequency signals. Finding the location of the discontinuities will provide good candidates for seed pixel. Wavelet transforms are suitable for this application because they perform a spatial-frequency decomposition of the image. It is similar to the Fourier transform, but with the advantage of retaining the spatial information. This is crucial for determination of the seed pixel location.

The method used is the non-decimated wavelet transform (NDWT). It performs the convolution of a wave characterized by defined shape and length on the image. Different frequency bands can be analysed by stretching the length of the wave and repeating the convolution process. Smaller waves capture the high frequency details (e.g. cracks). In this application, the Harr wavelet with one decomposition level was used.

The result is an image, called detail coefficients image, of the correlation of the wavelet with the image signal at the chosen decomposition level (i.e. frequency band). Since edges and noise are high frequency information, they also appear in the detail coefficients.

Some additional image treatments are then necessary to remove the edges and some noise. Cracks and edges have usually higher correlation coefficients than noise. A threshold coefficient is determined at the beginning of the analysis to transform the detail image into a binary image. This threshold is chosen to minimize the amount of noise without filtering out relevant crack pixels. The result of the NDWT method applied to the SH image (Figure 3) is shown in Figure 5.

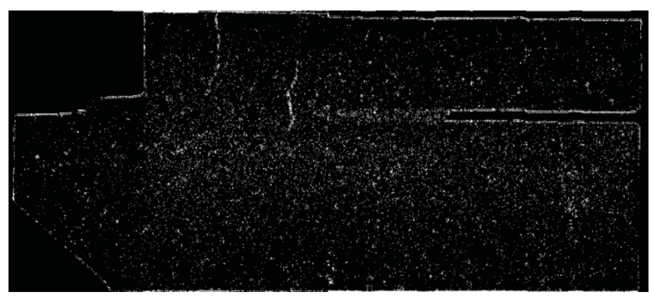
Figure 5 Result of NDWT after thresholding on SH image.

Seed pixels are selected by eliminating irrelevant pixel clusters and peripheral pixels in Figure 5. Most cracks in Figure 5 contain one or more clusters each generally composed of more than four pixels. Hence, only these clusters are potentially considered as a part of a crack and the centroid pixel in each cluster has been chosen as a seed pixel. The filtered version of Figure 5 is shown in Figure 6.

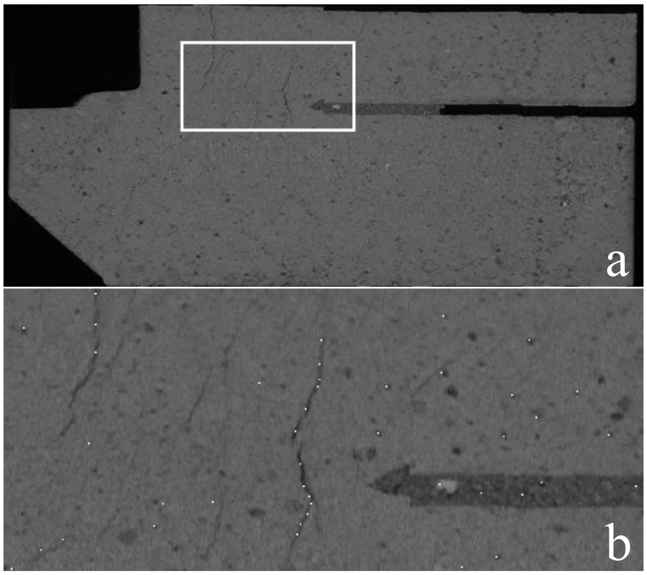

Figure 6 Position of seed pixels in SH image. a) Full scale. b) Zoomed image near the end of the slot.

Results and discussion

Non-modified crack detection method

The percolation process, as shown in Figure 4, requires seed pixels as input. The seed pixels have been identified following the procedures discussed previously for the two anode images (E and SH location). The numbers of seed pixels in E (Figure 3a) and SH (Figure 3b) are 153 and 150, respectively. They are mainly located in cracks and small porosities.

Parallel to the seed pixel detection, process parameters have to be set. They are first set in such a way that the initial window dimension *N=50*, the maximum window size *M=2N*, and the acceleration parameter *w=0*. The threshold for termination T_s is set to be 0.45 and the threshold on circularity F_c is set to be 0.25. The two thresholds are based on experimentation, as discussed in literature [3]. The choice of the size of the local window is also based on experimentation and can be difficult to set. The size *N* should be configured according to the size of cracks of interest. Considering the specific case of this work, the main problem is due to the large range of relevant crack sizes. The difference between the sizes of the smaller and larger cracks can indeed be of three to four orders of magnitude.

The percolation process has been applied on the SH image (Figure **3**) using two different initial window sizes to observe the effect of the window on the candidate regions. Figure 7 shows the result of percolation using the parameters listed previously with *N=50*. The crack detection method partially filled two cracks over five candidate regions. Increasing the initial window size to *N=75* helped the method to fill these two cracks, as shown in Figure 8. It also increased the number of irrelevant regions. It must be noted that in both case all candidate regions have circularity lower than the threshold value of 0.25.

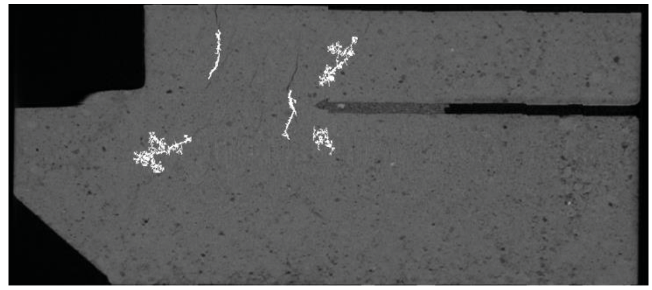

Figure 7 Results of percolation on SH image using the non-modified crack detection method proposed by [3] (*N=50*, *M=2N*, *w=0*).

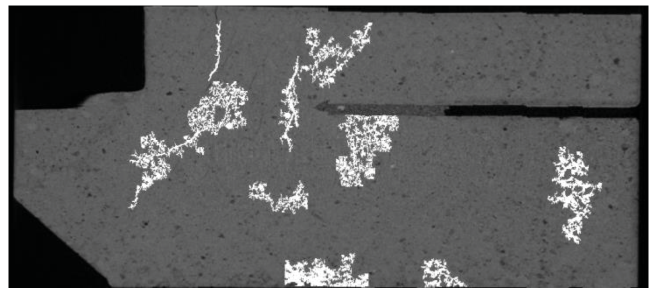

Figure 8 Results of percolation on SH image using the non-modified crack detection method proposed by [3] (N=75, M=2N, w=0).

The low circularity of the irrelevant regions (regions that are not a well-defined crack) is explained by the combination of two factors. First, the connectivity between pixels in those regions is low. There could be various explanations for this. One of them is that during the percolation process within the initial window (refer to reference [3] for the detailed algorithm), if there no pixel in D_c with brightness lower than the threshold value, the pixel in D_c with the lowest brightness is defined as D_c and the algorithm goes on. Second, such low connected regions have a high perimeter value while the area (number of pixel in the percolated region D_p) still relatively low. It thus results, as described in Eq. (2), in a low value of circularity.

Modified crack detection method

In addition to the circularity, other region properties can be used to improve the crack detection algorithm. The image process toolbox of Matlab® includes the *regionprops* function, which gives a set of properties of connected regions. It allows calculation of relevant properties of percolated regions such as the area and perimeter (which are both used to calculate the circularity in Eq.(2)). Most parameters of the *regionprops* function have been investigated using the crack detection method on a typical anode crack as presented in Figure 9. This figure shows the result of percolation at four different iterations, the first one being the seed pixel. The circularity evolution as a function of the iteration number is shown in Figure 10. By definition, the circularity cannot exceed 1. Circularity values higher than 1 (in Figure 10) is a known problem and is explained by errors in the area and perimeter calculation using the Matlab® functions. The errors are inversely proportional to the number of pixels. Threshold on circularity is however not used in first iterations (local window) when the number of pixel is low. The crack detection method performed well up to around iteration 65 where an unwanted porosity is included in the percolated region. A good correlation between this observation and the *MinorAxisLength* property has been found and is presented in Figure 11. *MinorAxisLength* is the minor axis of the ellipse that has the same normalized second central moments as the percolated region D_p. This property is proportional to the width of the region D_p. While Figure 10 did not show a significant increase of the circularity at iteration 65, Figure 11 clearly shows the effect of adding the porosity in the percolated region. The *MinorAxisLength* is thus a parameter that could improve the crack detection method.

The *MinorAxisLength* parameter can be inefficient in some cases. The *MinorAxisLength* of crack regions with very low circularity and having banana shaped geometry will be high. In this particular case, the crack may not be detected. The important cracks in anodes are however mostly of linear shape.

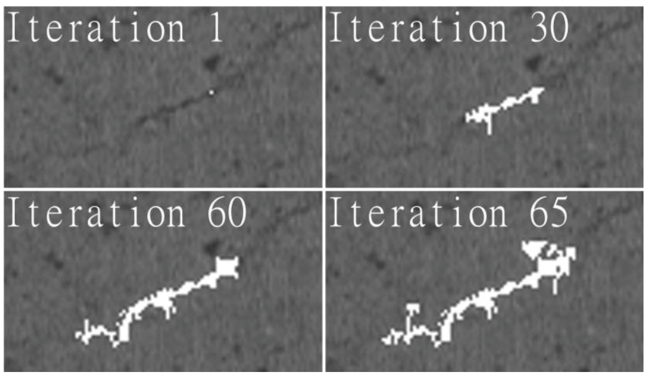

Figure 9 Example of percolation process.

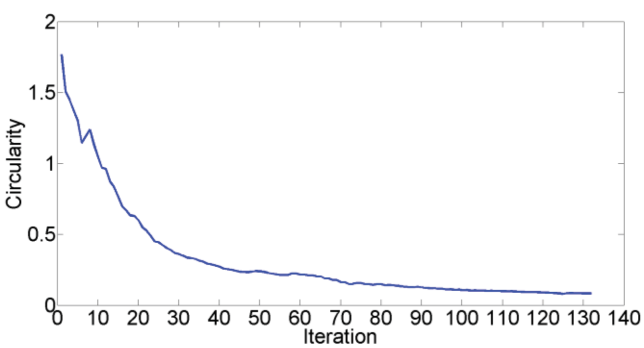

Figure 10 Evolution of circularity as a function of the iteration number during percolation process presented in Figure 9.

The crack detection method has been modified to introduce a threshold on the *MinorAxisLength* of the percolated region. The new threshold *Tmal* has been implemented at the end of the crack detection algorithm and thus acting like a filter on the candidate regions. The value of this threshold is based on experimentation and has been set at 20 pixels. The result of the crack detection method is shown in Figure 12. Some cracks still include some porosity that could not be avoided by the percolation process. However, the crack detection method, with the addition of the *Tmal* parameter, now correctly detects the most important cracks while eliminating the irrelevant percolated regions seen in Figure 7 and 8.

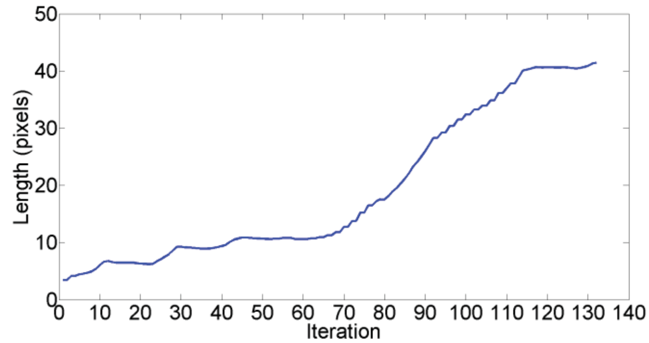

Figure 11 Evolution of minor axis length of the percolated region as a function of the iteration number during percolation process presented in Figure 9.

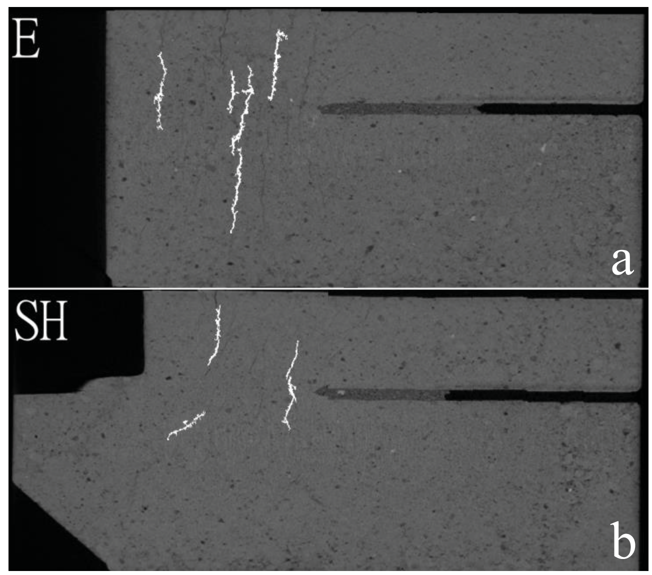

Figure 12 Final results of percolation on anodes images using a modified crack detection algorithm (N=75, M=2N, w=0, *Tmal*=20). a) Anode end (E location). b) Under a stub hole (SH location).

Table 1 presents some properties of the percolated regions identified as cracks in Figure 12. The area is the total count of pixels in all cracks (number of pixels in percolated regions) and is also expressed in surface area considering that the surface of a voxel is 0.6 x 0.7 mm^2. The surface ratio is the ratio of the crack areas over the total number of pixel of the sample or "carbon pixel" (pixels with zero brightness around the sample are not taken into account).

Table 1 Properties of percolated regions of Figure 12.

Images	Number of cracks	Area (pixels)	Area (mm^2)	Surface ratio (%)
E	4	2566	1078	0.67
SH	3	1164	489	0.28

Some cracks are still missed by the crack detection method. The reason is that the seed pixel detection process did not detect any seed pixel in these missing cracks. Further adjustment of the seed detection parameters is thus necessary.

Conclusion

Anode crack is a defect encountered during anode baking and can be used to evaluate anodes quality. Image processing tools are very efficient to achieve this goal. An existing crack detection method combing accuracy and low computation time was used. Percolation process of this method was mainly driven by the circularity of the region but was not sufficient in the present case. The algorithm was then tweaked by introducing a threshold on the *MinorAxisLength* of percolated regions to overcome the problem caused by the low resolution of anode images. With further adjustments of the seeding process, the output of the method for typical anode images (Figure 12 and Table 1) could then be used to estimate quality of anodes.

The anode used in this study was cut in several pieces (52). However, quality control does not require necessarily a large number of slices. Hence, only few slices located at specific locations, previously determined with studies similar to this one, can be used for this process.

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