Ultrasonics 89 (2018) 126–136

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Inspection of baked carbon anodes using a combination of multi-spectral acousto-ultrasonic techniques and principal component analysis

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ARTICLE INFO

Keywords:
Acousto-ultrasonics
Wavelets
PCA
Baked carbon anodes
Primary aluminium smelting
Defect detection

ABSTRACT

This paper reports on the application of an acousto-ultrasonic (AU) scheme for the inspection of industrial-size carbon anode blocks used in the production of primary aluminium by the Hall-Héroult process. A frequency-modulated wave is used to excite the anode blocks at multiple points. The collected attenuated AU signals are decomposed using the Discrete Wavelet Transform (DTW) after which vectors of features are calculated. Principal Component Analysis (PCA) is utilized to cluster the AU responses of the anodes. The approach allows locating cracks in the blocks and the AU features were found sensitive to crack severity. The results are validated using images collected after cutting some anodes.

1. Introduction

The Hall-Héroult electrolytic cells are widely used for primary aluminium smelting. In this process, large carbon blocks acting as anodes distribute the electrical current throughout the cells. They also participate in the electrolytic reduction reaction and therefore, they need to be replaced after a set cycle of about 20–30 days. The baked anodes are often manufactured on site using petroleum coke and coal tar pitch as the main raw materials.

A major concern in the aluminium industry is the declining quality and increasing variability of the anode raw materials. The frequent supplier changes made in order to meet quality specifications while reducing purchasing costs further contributes to incoming raw material variability. Variations in raw materials properties combined with changes in the anode manufacturing process conditions may create internal flaws such as compositional heterogeneities, a higher concentration and/or larger pores, and cracks within the anode blocks, which, in turn, affect the performance of the aluminium reduction cells by decreasing their energy efficiency and increasing the specific carbon consumption. The anode quality control scheme widely used throughout the industry consists of collecting core samples from baked anodes according to a well-established sampling plan, followed by core characterization in the laboratory. This control strategy is applied to a small proportion of the anode production (about 1% typically), because it is costly, time consuming, and damages the anodes (coring). In addition, the core samples themselves are not necessarily representative of the whole anode block which properties are known to be spatially anisotropic (a core sample is about 0.1–0.2% of the block volume). Furthermore, lab characterization results are often available after a delay of several days, which limits the application of feedback corrective actions to the manufacturing process in a timely fashion. Hence, there is a need for developing rapid and non-destructive techniques to assess baked anode quality before setting them in aluminium reduction cells.

Current research focuses on developing electrical resistivity measurement systems for individual green [1–3] and baked anode blocks [4,5] based on different technologies. These new devices provide measurements for the resistivity distribution within the anodes, a very important property affecting reduction cell performance. However, their capacity to detect and locate defects within them, and to identify and discriminate different types of flaws still need to be established. The defect diagnosis phase is crucial for decision making on what actions operators should implement on the anode manufacturing process and/or whether an anode should be rejected and recycled back to the manufacturing plant.

The acoustic–ultrasonic technique (AU) was considered to investigate various materials, for example [6–8]. Non-destructive evaluation based on acoustic signals and multivariate statistical techniques was also tested on different porous materials other than carbon anodes [9–11]. An apparatus, based on sonic wave propagation, was developed to measure the physical properties of refractory and carbonaceous materials including anode materials [12–14]. It was primarily designed

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https://doi.org/10.1016/j.ultras.2018.05.008
Received 19 October 2017; Received in revised form 19 February 2018; Accepted 15 May 2018

for characterizing the materials, but can also detect large flaws on small samples having simple geometries. A combination of acousto-ultrasonic techniques and PCA for data clustering was recently proposed for baked anode quality assessment [15–16]. This approach was tested on smaller anode parts (slices), and its ability to detect voids and to discriminate low-density regions (e.g., pores and cracks) from denser material was demonstrated. The present work reports on the first application of the method to a number of industrial-size anode blocks. The main objective consists of showing the potential of the methodology proposed for small anode parts [16] to discriminate damaged from healthy full-size anodes, and to locate cracks within the blocks. Although previous work [15–16] established that pores and cracks can be detected and discriminated (validated by X-ray CT Scan), this work focuses on crack detection since it is the most important anode defect, and the images used for validation do not allow characterizing porous regions with sufficient precision. Indeed, pores are always present in the anodes, even the healthy ones. A more porous anode would still be used in the aluminium reduction cells unless the pores are abnormally large, indicating a major problem with some manufacturing equipment. Such a situation was not observed in any validation images collected in this study.

The potential of the approach is demonstrated using two case studies. The first shows the capacity of the method to detect defects and assess their severity by focusing on damages located underneath the stub holes of the anodes. The second case study concentrates on the analysis of within anode variability in order to locate the defects and evaluate the anode block uniformity. The method is applied first to a set of 4 anodes having different "health" conditions to illustrate how defects are detected and located. Attenuation maps using all available data are then proposed to show how the inspection scheme could be implemented in practice.

2. Materials and experimental set-up

In total, 27 industrial-size baked anodes were obtained from the Alcoa Deschambault Quebec (ADQ) smelter. In order to test the proposed approach, it was necessary to select anodes of different quality including defect free anodes, and some containing defects of different types and sizes (severity). Since this task is difficult to achieve without destroying the blocks to get access to their internal structure, it was decided to sample anodes belonging to three groups, as shown in Table 1. The first group of anodes had defects visible from their external surfaces. For example, anodes A2, A3, and A7 contain large transversal cracks, and anodes A8, A12, and A13 show surface degradation mainly caused by burning of the material during the baking operation. The second group had no externally visible defect but were manufactured under different process conditions. Anodes A14 and A15 were produced during anode plant restart (after regular maintenance shutdown) whereas A16-A27 were baked in different known positions within the furnace where they have been submitted to a more or less severe thermal history. Indeed, temperature and heating rates are not uniform within the open-pit furnaces used to bake the anodes. Higher heating rates may lead to faster degassing of pitch volatiles, and increase both the number and severity of the cracks. The last group (anodes A1, A4, A5, A6, A9, A10 and A11) had no external defects but some of their manufacturing conditions could not be retrieved (i.e., unknown baking positions).

Table 1
Anode numbers and description.

Anode description	Anode numbers
Visible external defects	
Transversal cracks	2, 3, 7
Degradation and burn	8, 12, 13
Produced under different conditions (no external defects)	
Start-up anodes	14, 15
Different baking positions	16–27
No external defects but baking position unknown	1, 4, 5, 6, 9, 10, 11

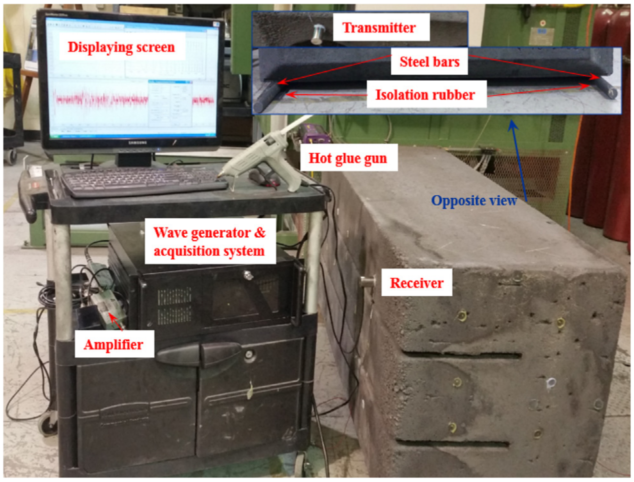

Fig. 1. Experimental acousto-ultrasonic measurement set-up.

The experimental set-up shown in Fig. 1 was used to measure the propagation behavior of the mechanical waves through the anodes. First, the blocks were flipped on their side onto two steel bars isolated from environmental vibrations using rubber parts. This allowed to easily access both the bottom and the top of the anode for manually mounting the transducers. Flipping of the anodes would not be necessary using an industrial automated set-up. A computer generated acousto-ultrasonic frequency-modulated wave was sent through the material by a transmitter in order to excite the anode block on one surface, and the attenuated response wave was recorded by the receiver located *vis-à-vis* the transmitter but on the opposite surface. Both acoustic transducers were held in place on the anode using hot glue. The excitation frequency range was selected after preliminary work was made on anode slices cut along the height of an industrial-size anode [15,16]. Since the slices were obtained from the same material as the one studied in this paper, and they were excited along the anode height (similar as in this work), the same excitation frequency range was used as a starting point for this study. It was later determined that the 100–200 kHz frequency band was the most relevant range for detecting and analyzing anode defects on the full-size anodes. Signals at lower frequency than 100 kHz were not sensitive to defects, and those having a higher frequency than 200 kHz were mostly attenuated by the large anode blocks. Also note that the transducers used in this study can only transmit or acquire compressive waves. Shear waves have not been studied in this work.

The anodes were tested in two directions (transversal and longitudinal) as shown in Fig. 2 to assess whether it is possible to discriminate defects having different orientations in the block (e.g., cracks oriented horizontally, vertically or diagonally). Indeed, the mechanical wave should be more attenuated by cracks oriented in the perpendicular direction to the wave propagation front for a given defect size. The measurements were collected sequentially, at 29 different positions on each anode as shown in Fig. 2 using a single pair of transducers. For the excitation points 1–21, the transmitter and receiver were mounted on the top and bottom surfaces, respectively, in order to measure the acoustic wave attenuation across the anode height. The attenuation along the length of the anode (long side) was obtained from the last 8 excitation points (22–29). Hence, the excitation points 1–21 should better capture defects mostly oriented horizontally while points 22–29 should capture vertically oriented defects more clearly. Diagonal cracks are expected to affect the signal in both directions. Some excitation points could not be tested for a few anodes because of physical damage at that location (e.g., sensors could not be mounted due to piece broken