A Numerical Analysis of the Mechanical Behavior of Coke Aggregates under Monotonic and Cyclic Loadings

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Abstract

Carbon anodes are part of the chemical reaction to reduce alumina in the Hall-Héroult process, of which coke aggregates make up a major part (about 85%). The study of the mechanical behavior of coke aggregates not only leads to a better understanding of the deformation mechanisms of granular materials under a compressive loading, but also can identify potential causes of structural defects in carbon anodes, such as horizontal cracks. On the other hand, thanks to recent advances in high performance computing, it is possible to simulate the behavior of granular materials such as coke aggregates with respect to the interactions between particles. Therefore, in this work, we investigate the most important factors affecting the mechanical behavior of granular materials, such as the particle size distribution as well as the rolling resistance between the particles, a parameter considering the particle shape through the discrete element method (DEM) modeling. Considering carbon anodes produced by the vibrocompaction process, the effects of frequency and number of cycles of this process on the final density of the coke mixture are investigated. The results reveal that by adding the small particles to the mixtures, the reversible deformation decreases through the monotonic loading condition. In addition, increasing the rolling resistance decreases the amount of permanent deformation in the monotonic loading condition. On the other hand, by increasing the frequency of vibrocompactor, the permanent deformation is enhanced. Moreover, a comparison between monotonic and cyclic loading conditions states that, although increasing the strain rate reduces the permanent deformation in the monotonic loading, in the cyclic loading, increasing the strain rate increases the permanent deformation.

Keywords: Carbon anode, Discrete element method simulation, Monotonic loading, Cyclic loading.

1. Introduction

Carbon-like materials such as the anode and the ramming paste are crucial parts of electrolysis cells in the Hall–Héroult process. It is shown that 6.5% of the voltage drop across the cell is due to the voltage drop associated with the anode assembly [1]. Anode quality characteristics, such as density, electrical resistance and reactivity affect not only the energy efficiency of aluminum production but also the amount of carbon consumed and the resulting environmental concerns [2]. The carbon anodes are composed of two major parts, i.e., the dry coke aggregates (85 wt.%) and the coal tar pitch (15 wt.%). Due to the limited resources for anode fabrication, changes in the properties of raw materials, and consequently the parameters of the anode production process, consistent, homogeneous, and high-quality anode production are a major challenge for the anode fabrication. It should be noted that the main parameters of the anode vibrocompaction process are the amount of pressure, speed, duration of formation, and the temperature of the process.

Coordination of the anode production parameters with new raw materials is another problem of carbon anode production.

The carbon anodes in most aluminum smelters are produced by the vibration compression process. It has been shown that the anodes produced in this process have a higher quality compared to the monotonic compaction process [3]. Azari et al. investigated the effects of raw materials, such as particle shape and coke/pitch ratio, on the mechanical behavior of green anodes during the monotonic compaction [2, 4]. Thibodeau et al. determined the mechanical behavior of anode paste during the compaction process at 150 °C using the monotonic and cyclic compaction tests [5]. Based on the experimental results, they showed that a small axial stress level in the quasi-static regime leads to a significant compression of the green anode before skeletal formation. After that, the stress required for additional compaction increases. In addition, by performing cyclic compaction experiments with a linear loading/unloading rate (0.2 MPa/s) on the dry coke aggregates, Thibodeau et al. emphasized that a combination of hardening-softening behavior during each loading cycle [6]. Based on the results of experiments on the anode paste, Kansoun et al. investigated the mechanical behavior of a commercial-grade carbon paste used in the aluminum industry during the monotonic and cyclic compaction tests [3]. They showed that the stress required for the anode compaction at the cyclic loading is less than the monotonic one. On the one hand, they claimed that the strain rate does not affect the anode paste behavior in the quasi-static regime. On the other hand, they declared that the strain rate plays a negative role in the dynamic regime compression of anode paste. It means that for reaching the target density, more pressure is needed. Extensive research has also been done on the mechanical behavior of hot asphalt mixtures, which have a similar composition to anode paste mixtures [7]. Accordingly, the mechanical behavior of asphalt mixtures under cyclic loads includes important phenomena such as (1) hardening-relaxation behavior, (2) particle rearrangement, and (3) the permanent deformation due to cyclic loads is significantly greater than the permanent deformation due to monotonic loads [8]. However, investigation of production parameters affecting the anode quality through laboratory tests has problems such as opacity of the anode paste and high temperature of the production process [9, 10]. Hence, the numerical modeling of carbon anode paste can be considered as a practical solution.

Many attempts have been made to model the mechanical behavior of the anode. Chaouki et al. have proposed a constitutive law to simulate the anode paste during the compaction process [11]. Although this model can reveal the density gradient due to the stub-hole, it is not capable of demonstrating the formation of localized bands [12]. It should be noted that localized bands refer to an area of the material that has undergone non-uniform deformation, in that the deformation is mainly concentrated in it [12]. This limitation stems from the fact that the granularity nature of the anode paste cannot be considered by phenomenological models such as finite element methods [13]. Moreover, many research works have been done to investigate the behavior of anode paste using the discrete element method (DEM), which considers grains as the basic element from which the mechanical behavior of granular materials originates [14]. DEM has shown the ability to successfully simulate some properties of the anode coke aggregates, such as the bulk density [15] and the electrical resistivity [16].

coal-tar pitch in the vibrocompaction process of anode paste will be explored by using DEM simulation.

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