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ScienceDirect

Ceramics International 40 (2014) 5473–5480

CERAMICS INTERNATIONAL

www.elsevier.com/locate/ceramint

The importance of surface hydration and particle shape on the rheological property of silica-based suspensions

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Received 23 August 2013; received in revised form 28 October 2013; accepted 28 October 2013
Available online 6 November 2013

Abstract

Two types of ball milling methods, wet planetary ball milling and dry tumbling ball milling, were used to grind fused silica powders for the preparation of silica-based suspensions in this experiment. The effect of surface hydration and particle shape caused by the two milling methods on the slurry rheology was investigated. The results showed that, with similar particle size distribution, the viscosity of the suspensions prepared from the powders milled by wet ball milling ranged from 275 mPa s to 311 mPa s within 20 min and the suspension exhibited a continuous shear thickening behaviour whereas the viscosity of the suspensions prepared from the powders milled by dry ball milling ranged from 69 mPa s to 74 mPa s and the suspension exhibited a shear thinning behaviour first, and then exhibited a slightly shear thickening behaviour. The reasons were attributed to the differences in surface hydration and particle shape. It was postulated that the two factors affected the slurry rheology through the modification of particle interactions during the flow of high concentration suspensions.

Keywords: Ball milling; Particle shape; Silica ceramic; Slurry rheology; Surface hydration

1. Introduction

Silica ceramic is a kind of promising material, which is widely used in aircraft materials, metallurgy, thermal protection system, etc. In all types of shape forming techniques of ceramic materials, such as slip casting and gel casting, suspensions with low viscosity and appropriate fluidity are highly desired, because the rheological property of the concentrated suspensions plays a major role in controlling the shape forming behaviours and optimising the properties of a green body [1,2]. Although tremendous progress in dry shaping techniques has been made in recent years, the major fabrication method for the silica ceramic, for example, silica crucible and silica casting pipe, is still the wet shaping technique. Therefore, the research on the slurry rheology is still of great significance.

Currently, the most widely used fabrication method in wet shaping techniques for silica ceramic is the slip casting technique. The slip casting is characterised by simple devices and low cost, and can be applied for the fabrication of large and complex products. For this kind of forming technique, much work has been done considering the effects of particle size, particle size distribution and solid loading on the rheological property and densest particle packing. Olhero and Ferreira [3] investigated the effect of particle size distribution on the slurry rheology and particle packing in a silica-based suspension. They concluded that the viscosity of suspensions increased with the adding of fine particles and the increase of size ratio enhanced a shear thinning behaviour of the suspensions. It is universally accepted that the presence of coarse particles in the suspension enhances a shear-thickening behaviour [4]. However, this conclusion cannot be generalised for all the systems. As a matter of fact, for a given solid loading, bimodal particle size distribution enables a significant decrease in the viscosity of the suspension [5–7]. Concerning the solid loading, there is no doubt that the viscosity increases with the increasing solid loading [8]. In addition to these factors, the preparation technology of the powders also has a significant impact on the property of the particles, consequently, influencing the rheological property of the suspensions. However, the effect of powders preparation methods on the slurry rheology is seldom reported.

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0272-8842/$ - see front matter
http://dx.doi.org/10.1016/j.ceramint.2013.10.135

At present, the most simple and economic method for the preparation of powders is ball milling. In general, conventional ball milling can be divided into two types, namely wet ball milling and dry ball milling. Wet ball milling with higher milling efficiency is the most common method for the preparation of the powders [9–11]. The shortcoming of this kind of milling method is that the powders after wet ball milling need to be dried to remove the water or other liquid media, which greatly increases energy consumption and costs. Dry ball milling mainly depends on the crushing and grinding effect of the grinding media to achieve powders comminution. Because of the adsorption effect between the particles during the later stage of dry ball milling, the particles tend to cohere with each other, which would significantly reduce the milling efficiency. A great deal of work has been done considering the influence of wet and dry ball milling on the fineness and the size distribution of the particles [12–14]. However, they did not pay much attention on the surface hydration and the shape of the milled particles which are also fundamental parameters to optimise the rheological property and shape of an optimal size distribution. Yuan and Murray [15] studied the influence of particle morphology on the rheological behaviour of kaolin suspensions with high solid loading. They concluded that the spherical halloysite showed the lowest viscosity, followed by the platy kaolinite and the tubular halloysite. These results clearly demonstrate that the particle shape is an important parameter for slurry rheology.

The present study is intended to illustrate the effect of surface hydration and the particle shape of SiO_2 powders caused by wet and dry ball milling on the rheological property of the suspensions. A vibrating slip casting technique was employed to find the role of experimental variables on the rheological property of the suspensions.

2. Experimental

2.1. Starting materials and powders preparation

The fused silica (SiO_2) powders (99.9%, Ceradyne, Inc., USA) with the particle size between 180 and 270 μm and lactic acid (85–90%, Tianjin Comio Chemical Reagent Co. Ltd., Tianjin, China) used as the dispersant and pH adjustment agent were selected as the raw materials in this study.

Two types of milling methods, wet planetary ball milling and dry tumbling ball milling, were adopted to prepare finer SiO_2 powders with certain size distribution used in the slip casting. Wet ball milling was performed in polypropylene bottles at 750 rpm in distilled water (water to powder weight ratio = 0.39:1) using zirconia grinding media (average diameter 6 mm, balls to powders weight ratio = 2:1). Dry ball milling was carried out under the same conditions (750 rpm, zirconia balls grinding media with an average diameter of 6 mm, and balls to powder weight ratio = 2:1). The particle size and size distribution were mainly controlled by the milling time. The milled fused SiO_2 powders were named W (W-milled by wet planetary ball milling) powders and D (D-milled by dry tumbling ball milling) powders, correspondingly.

2.2. Slurry preparation

The powders W-6 h (milled by wet planetary ball milling for 6 h) and D-14 h (milled by dry tumbling ball milling for 14 h) with similar particle size distributions and average sizes were selected to study the influence of surface hydration and particle shape on the rheological properties of the suspensions. Slurries containing 65 vol% of milled fused silica powders were prepared by dispersing W-6 h powders or D-14 h powders in distilled water in the presence of different amounts of lactic acid. The slurry components were mixed in polypropylene bottles kept under rotation (600 rpm) in a planetary mill in the presence of zirconia grinding media (6 mm diameter and balls to powders weight ratio = 2:1). To minimise the disturbance during the forming process, constant solid loading and forming conditions were maintained in this study.

2.3. Particles and slurry characterisation

The particle size analysis of the fused silica was performed with a Malvern Laser Particle Size Analyser (Mastersizersiong BED, Malvern Ltd., UK). A scanning electron microscope (Nanosem 430, FEI, Inc., USA) was employed to observe particle morphology and estimate the size of the particles prepared from wet and dry ball milling. MATLAB software and concerning image processing software were used to estimate the average roundness of the particle. The surface charge density of silica was measured with a zeta potential analyser (Zetasizer Nano ZS, Malvern Ltd., UK) to research the effect of milling and lactic acid on the zeta potential of SiO_2 powders. X-ray photoelectron spectroscopy (PHI1600, Perkin Elmer, Inc., USA) and Fourier Transfer Infrared spectroscopy (NEXUS TM, Nicolet, Ltd., USA) were used to investigate the state of surface hydration of the SiO_2 particles.

Rheological measurements were carried out using the rotational viscosimeter (NDJ-8S, China). The measuring configuration adopted was a 2# rotator considering the viscosity range of the silica-based slurry and the rheological measurement was performed with the spindle rotation speed from 3 rpm to 60 rpm. Before the rheological measurement, the slurry was kept stirring with magnetic stirring apparatus at high rate for 2 min in order to transmit the same rheological history to the whole suspension.

3. Results and discussion

3.1. SiO_2 particles characterisation

3.1.1. Particle size distributions

Although there are differences between wet planetary ball milling and dry tumbling ball milling in milling efficiency, particle size and particle size distribution, similar particle size distribution can be achieved by controlling the milling time and the milling conditions. The particle size distribution curves of fused SiO_2 powders ball milled for different hours under wet and dry conditions are presented in Fig. 1. It can be seen that under both wet and dry conditions, particles become smaller