Micro-Mineral Particle Slurry Rheometry

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In mineral flotation operations, the mineral slurry is usually treated via grinding, agitation, flotation, and transportation, and the micro-particle slurry is often mixed with chemical reagent (mill and agitation tank) under such conditions, with air bubbles being separated under certain shearing fields in water-used equipment, such as a flotation cell or column. One characteristic of the micro-mineral slurry is polydispersity, including size and shape.

slurry rheology froth rheology grinding flotation fine particle

1. Introduction

1.1. The Characteristic of Mineral Slurry

Froth flotation has been the most widely used approach for treating complex low-grade and finely disseminated ores. Flotation pulp consists of micro-particles with a certain grinding fineness, which is generally expressed as the mass ratio (%) of less than 0.074 mm/the total grinding product (the grinding fineness depends on the target mineral liberation degree) [1]. In mineral flotation operations, the mineral slurry is usually treated via grinding, agitation, flotation, and transportation, and the micro-particle slurry is often mixed with chemical reagent (mill and agitation tank) under such conditions, with air bubbles being separated under certain shearing fields in water-used equipment, such as a flotation cell or column [2].

One characteristic of the micro-mineral slurry is polydispersity, including size and shape. The particle size distribution of the micro-mineral slurry usually covers a quite large range, from less than 1 nm to larger than 1 mm, for there exists a series of dispersed components including organic/inorganic molecules, ions, macromolecules, colloids of mining reagents, suspending particles, and settling aggregation or grains [3]. For metallic minerals and coal particles in handling plants, the particle size in slurry is on average approximately 100 μm [4]; for some clay minerals, the particle size in handling operations is mostly less than 10 μm [5]; but for clay mineral-based materials, the particle size could decrease to less than 0.1 μm [6]. As for the particle shape, most of the mineral crystals after crushing and grinding have a globule-like morphology. For the nesosilicate minerals and coal, the particles in the processing operation are usually of an irregular angularity [7]. For the phyllosilicate minerals such as talc, graphite, and mica, particles in slurry are often in lamellar or platy, while the chain silicate minerals, such as chrysotile and serpentine, are often in a fibrous shape or have a silky morphology [8][9]. In a micro-mineral slurry, various kinds of minerals of different sizes and shapes always exist. Therefore, the complexity of the micro-mineral particle slurry makes it quite difficult to describe the size and shape using one or two of the single mineral characteristics.

Another typical characteristic of the micro-mineral slurry is the complex interactions among the different components, including solid-solid interactions, reagent-solid interactions, and dynamic bubble-liquid-solid effects. It has been widely acknowledged that these interactions are closely correlated to the solid content. For slurry with relatively coarse mineral particles and a small solid-to-liquid ratio, the particle interactions mainly manifest as simple mechanical actions, such as mutual friction, collision, and compression [10][11][12]. For slurry with relatively fine mineral particles and a high solid content, the surface force that originates from solid surface phase change via chemical reactions or reagent adsorptions determines the particle interactions. For slurry with agglomerated fine particles or flocs, the complex interactions should also include the parcel effect between the new-born flocs and primary fine slimes as well as the scrubbing effect between the new-born flocs and primary coarse grains [13][14][15]. For the particles with different shapes in slurry, it was thought that simple forces such as attractive or repulsive actions constitute the main particle interactions between the globule-like particles and irregular angular particles [16][17]. The solid content plays an important role in deciding the particle interactions, and it was widely thought that a high solid-to-liquid ratio could lead to more complicated slurry properties, especially for the fine mineral flotation process.

During the flotation operations, the particles in the slurry are not totally dispersed or isolated, and the slurry is not a homogeneous water system with stable flowability. The complex interactions among these particles depend on particle collision, aggregation, dispersion, floating, sinking, and transportation, which mainly determine the flow and deformation behaviors during the processing operations and have been understood using slurry rheology.

1.2. Rheology in Mineral Processing

Rheology is the science of studying the flow and deformation behaviors of fluid materials. The rheological parameters, such as viscosity, yield stress, viscoelasticity, have been demonstrated to indicate the particle interactions and the particle structures in a certain flowing field [2][17]. These common parameters are calculated by analyzing the shear rate vs. shear stress curves, shear stress vs. shear strain curves, and viscous modulus vs. elasticity modulus curves measured using a rheometer [18][19]. As a typical solid-gas-liquid suspension with polydispersity and complex interactions inside, the flow and deformation performance of micro-mineral processing slurry is usually determined using non-Newtonian rheology, since it displays common rheological behaviors including shear thickening, shear thinning, shearing yield, and compressing yield [20][21]. Therefore, slurry rheology has long been used as an effective parameter to understand the particle interactions and optimize processing efficiency, especially for fine mineral treatment [22][23].

Generally, the studying of mineral slurry rheology started when the effects of high viscous fluids formed by very fine mineral particles on the grinding rate and efficiency were first noticed [24]. At first, it was found that there existed a remarkable viscosity effect on the grinding process when the dilatant fluid, pseudoplastic fluid, or Bingham fluid were formed on a large scale inside the ball mill or rod mill [25][26]. Afterwards, in other processes, including dense medium separation, bevel flow separation, magnetofluid separation, and froth flotation, slurry rheology not only provided information about the very complicated inter-particle interactions in processes related to the flow of mineral slurry, but also explained the certain influences on the subtle processes of these operations [20].

2. Micro-Mineral Particle Slurry Rheometry

The rheological measurement instruments in mineral processing have been developing and promote the development of slurry rheology. In early times, slurry rheology was mainly developed via naked-eye observations or manual qualitative testing, such with the spatula test, touching test, or flow cup test. These measurement results were useful and effective for directly judging the viscosity and elasticity of tested materials. However, these qualitative testing results could not provide the dynamic rheological information for measuring the shearing field or shearing intensity. For this, the viscometer and rheometer, which could quantitatively measure the shear rate and stress, were developed successively. So far, most of the rheological measurements have been completed using the two kinds of rheology equipment.

2.1. Rheological Measurement Using Viscometers

Around the 1990s, various kinds of viscosimeters that could provide the flowing and deformation performance of slurry under several fixed shear rates were widely used, such as the rotational viscometer and capillary (tube) viscometer [27][28]. For industrial slurry, the rotational viscometer has been proven to better suit than the capillary viscometer for its measurement principle [18][29]. The rotational viscometer calculates the viscosity by measuring the torque that resists the deformation and flow of slurry and recording the rotation rate of the measurement fixture dipped into the suspensions [19][30][31]. The viscosity value is determined by transferring the torque and rotation rate to the shear stress and shear rate, respectively, based on device parameters such as shape, surface flatness, volume, dip angle of the measurement fixture, and sample holder [32][33].

Though the rotation mode of the viscosimeter could reflect the actual shear conditions in the mineral processing operations, such as agitation in the tank and flotation cell, it could only conduct single-point measurement services. Only the viscosity value under several limited and several fixed shear rate values (usually 4 to 6 fixed shear rate values) could be obtained. However, the available shear rate selections for the rotational viscometer do not always reflect the actual shear rate distributions in the shear fields of mineral processing operations. They may deviate significantly when the micro-mineral slurry presents shear thickening, shear thinning, and other specific rheological performances.

2.2. Rheological Measurement Using Rheometers

In the late 1990s and the 21st century, corresponding rheometers fixedly assembled with computers appeared and made it possible for the continuously variable measurement to overcome the drawbacks of the viscometer. Similar to the rotational viscometer, the rotational rheometers also measure the torque applied on the measurement tools and its rotational speed and utilize the torque and rotation rate values to calculate the rheological parameters [28][34]. However, different from the viscometer, the rotational rheometer has a continuous control system that can measure the shear stress at any designed shear rate, making it more convenient for simulating the exact shear conditions under any constant or variable moving or agitating speed [32][35][36]. What is more, the rheometers can measure the shear strains of the slurry under certain shear conditions, which provide the viscous and elastic property of the aggregated or dispersed micro-mineral slurry as well as the information on the very subtle dynamic changes in the internal particle structures of the slurry under a gradually applied yield stress [37][38].

There have been many measuring tools used for rheology measurements, such as coaxial cylinders, cone plates, parallel plates, vanes, and impellers. For homogeneous or uniformly dispersed solution systems, coaxial cylinders, cone plates, and parallel plates could accurately measure the rheological properties. For typical heterogeneous systems such as mineral slurry, vanes and impellers have been demonstrated to be more applicable because these tools could effectively mix the dispersed micro-mineral particles before rheology measurement and avoid the settling problems of particles or aggregations when it comes to the measurement processes.

2.3. Developments in Rheological Measurement: Dynamic Oscillatory Techniques

There has also been a recent rise in the measurement of viscoelasticity of mineral slurry, mainly realized using dynamic oscillatory techniques and which could help distinguish cross-linked network structures from isolated clay aggregates [36]. Unlike the viscosity measurement or yield stress calculation, the dynamic oscillatory techniques aim to characterize the particle network or specific superstructures by measuring the viscous modulus and elastic modulus of the slurry in the linear elastic region. Strain sweep and frequency sweep were suggested to be two main measurement methods used to clearly see the degree of dispersion and the strength of the inter-particle association in the slurry [37].

The fundamental theory of using the viscous modulus and elastic modulus to describe the multi-particle structures and dispersed particles is the viscoelasticity of network structures or super spatial structures formed by micro-mineral particles. When the micro-particles transform into network structures or other super-specific structures, the new aggregates can obtain a solid-like elasticity, which cannot be effectively detected and quantified via viscosity or yield stress measurements [38]. Therefore, the elastic modulus parameter was proposed to represent the elasticity property. The viscous modulus was used to characterize the viscous attraction among the particles in the multi-particle structures under relative static hydrodynamic conditions. One of the advantages of the dynamic oscillatory rheology test is that the micro-mineral slurry is not shear-destroyed. Only deformation and linear disturbance of the micro-mineral slurry happens using this measuring mode, and it is possible to determine its variation continuously. Another advantage of the oscillatory rheology test is that the testing results are independent of the shear rate, making it more objective when making a comparison [37][38].

In short, the development of micro-mineral particle slurry rheometry is heading toward the online and simultaneous characterization of inter-particle interactions, including both the viscous resistance and viscous attractions during the mineral processing operations.

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