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Onset of abrasive wear of boundaries in concentrated suspension flow

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ABSTRACT

A predictive model for abrasion of boundaries by a flowing suspension is developed. The basis of the model is that wear arises when the local normal stresses exerted by particles in the shear flow exceed the material strength of the boundary. From this threshold stress, one deduces an onset shear rate at which abrasion will be observed for a given particle loading and liquid viscosity. An apparatus was designed to examine the effect of particle concentrations of 30–50% by volume particles at varying flow rates using materials of varying surface yield strengths. This provided a wide range of conditions to study the model predictions, using soft substrates. Agreement of model and experiment is good.

1. Introduction

Abrasive Flow Machining (AbFM) was first described by McCarty [1], and has been developed as a technique for deburring and polishing. Because of its ability to machine interior and curved surfaces, it is considered as a convenient surface finishing process. Over the last three decades, the AbFM method has been studied experimentally [2] and theoretically [3–5], as has been recently reviewed [6,7]. Recently, similar techniques such as magneto-rheological abrasive honing (MRAH) [8] and magnetorheological finishing (MRF) [9] have been studied.

Theoretical studies of the AbFM process usually calculate the stress that the particles apply to the surface first. This stress is typically assumed to be provided by particle inertia and slurry non-hydrodynamic stresses. The applied stresses are then compared to the mechanical strength of the surface to establish a relationship between the slurry flow parameters and the onset of surface damage, e.g. scratching. Slurry parameters may include size, shape (acicularity or local sharpness), and concentration of particles, slurry viscosity, and applied shear rate.

In many studies the fluid mechanical stress, i.e. the rheology of the material, is ignored because it is assumed negligible compared to the inertia stresses due to high particle velocity. However, when the viscosity of the slurry is high, the bulk suspension rheology can be critical and may be used as a control variable. The central concept of the present study is the demonstration that the suspension rheology may be compared to the mechanical strength of a wear part in order to predict boundary wear due to a flowing suspension (more commonly termed slurry in applications such as AbFM). Haan and Steif [10] were very perceptive in initiating investigations of this sort, focusing on the dispersive pressure exerted by the particles; the particle pressure is now a well-established concept [11,12], and here their approach is improved by significant recent advances in description of both the solid mechanical and suspension rheology aspects of the method. In the following, we provide a brief review of concepts related to the theory required to develop the model applied in comparison to experimental studies in this work.

The suspension stresses arise due to the particle interactions through a viscous fluid, as well as through non-hydrodynamic forces. Under the typical conditions of interest where the abrasive particles do not show appreciable Brownian motion (which typically means larger than about a micron) these non-hydrodynamic forces may be due to surface interactions due to charges, or actual surface contact. Surface contact is likely to be an important factor in highly concentrated slurries (at solid fractions $\phi > 0.5$ in particular) as recent work shows that the development of a contact network can lead to extremely large viscosity and normal stresses [13]. For present purposes, it is most important that the flow stress depends on the fluid viscosity (even when contact occurs, the base fluid viscosity is a critical parameter), and the rheology is non-Newtonian. In particular, the suspensions exhibit normal thrust: the particles are driven to dilate by the motion and the “particle pressure” driving this dilational tendency is resisted by the boundaries. The particle stresses can be calculated based on correlation of experimental data in the Zarraga et al. [14] or the theoretical modeling of Morris and Boulay [15], as the two are similar in the essential features; this is particularly useful for the purpose of basic analysis and provides a framework for applying the measured stresses for suspensions used in an abrasive flow application.

Understanding of the microscopic basis for the non-Newtonian rheology of slurries and suspensions has advanced greatly over the

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last two decades. Morris [16] reviewed the role of the microstructure of concentrated suspensions and the role it plays in developing the non-linear rheological properties, in particular normal stresses, which we relate here to slurry-induced wear. A critical point made clear by the microstructural analysis of the rheology is that the local stresses in the mixture flow may be much larger than the average (or bulk) suspension stress, in particular at points of close approach of particles. The same concept applies for particles at the boundary: the local stress between a particle and the wall will far exceed the mean stresses (both shear and normal) applied by the suspension to the wall. Thus, the individual particles act as amplifiers of the bulk stress in terms of their effect on the boundary. Understanding this effect is critical to accurate prediction of the onset of abrasive wear induced by flow of concentrated suspensions of solid particles. In the present work, the basic concepts are developed for spherical particles; clearly there is a qualitatively higher level of stress amplification and larger wear at a given bulk flow condition associated with particles with sharp edges (acicular particles). This is a topic that deserves study beyond that described here.

Turning now to the deformation of the surface, the indentation of a sphere into a surface was first developed by Hertz [17] in 1882. The Hertz model is for the elastic regime, i.e. it is valid up to the onset of plastic deformation of the substrate. Later, the Hertz model was developed in plastic and elastic regimes for different forms of indentation, as summarized by Johnson [18]. The models can be divided into two main groups. In the first, it is assumed that the sphere is a rigid body, which penetrates the surface. In the second, the sphere is on the surface as an asperity and is deformable. Jackson and Green [19] named the first and second models “indentation” and “hemispherical deformation,” respectively. The latter group is used to describe a wear process, with a good example being the Greenwood and Williamson model [20]. These models, as described by Johnson [18], are simple and analytical, allowing ready application of advanced differential equation solving techniques [21] or finite-element methods [19]. Some work has been done to model the indentation of spheres into surfaces by FEM [22,23], with a notable example published recently by Song and Komvopoulos [24].

In this work, we take advantage of the developments of both solid and fluid mechanical models to relate the bulk flow properties of a suspension or slurry to its capacity to impart surface damage or to perform polishing at the boundary of the flow. In particular, we calculate the necessary stress to indent or scratch the surface and relate this to the shear and normal stresses induced by the flow in a concentrated slurry. This provides a prediction of the minimal particle loading at a given shear rate, for example, to result in plastic surface deformation, which is an essential event for the onset of surface wear. An experimental apparatus was designed and built to analyze the surface damage induced under a range of conditions, and the results of the experiments largely support the validity of the calculations.

2. Experimental procedures

2.1. Apparatus

In designing the apparatus used in this work, there were specific goals. First, the shear rate should be variable with sufficient resolution to allow an accurate determination of the shear rate (or stress) at which damage in the form of surface scratching begins. Second, since the particle concentration is an important parameter that affects apparent viscosity and non-hydrodynamic forces, particle migration [15] should be minimized.

To satisfy these demands, an annular pressure-driven flow apparatus was designed. The inner and outer cylinders were machined from acrylic cylinders with the geometry shown in Fig. 1. To hold the inner cylinder in place, the two ends of the outer cylinder were threaded and two washer-type cylinders, each with a hole in its center, were threaded and screwed into the outer cylinder. The central holes in the washer cylinders aligned the inner cylinder concentric with the outer cylinder. Three grooves were machined on the surface of the inner cylinder along its entire length with depth and width of 1.5 mm and 3 mm, respectively; these grooves were used to hold wear samples, and were situated 120° apart from each other. For the orientation shown in Fig. 1, the suspension enters at the left side of the apparatus, and flows left to right. The applied shear rate increases in the zone where the outer cylinder inner radius decreases linearly. We define the x-axis coincident with the cylinder axis, with its origin at the beginning of the zone of decreasing radius, as shown in Fig. 1. At the end of the zone of decreasing gap width, at $x=80$ mm, there begins a zone which we call the “choke”, with constant distance of 1 mm between the cylinders. The maximum shear rate is found at the end of the varying width zone and throughout the choke zone. The scale of the shear rate is controlled by the imposed flow rate, while its variation is set by the apparatus geometry.

To drive the flow, a large syringe was built with an aluminum cylinder of diameter 115 mm and length 500 mm used as the syringe barrel. This barrel was paired with a closely-fitting piston, which was driven by an Instron 5582 (tensile test apparatus), with the force to drive the flow determined by the instrument load cell. The outlet of the syringe was connected by four tubes to distribute the suspension to equally spaced locations around the axis of the test section. The maximum force available to drive the flow was 100 kN and the speed range was 0.001–500 mm/min.

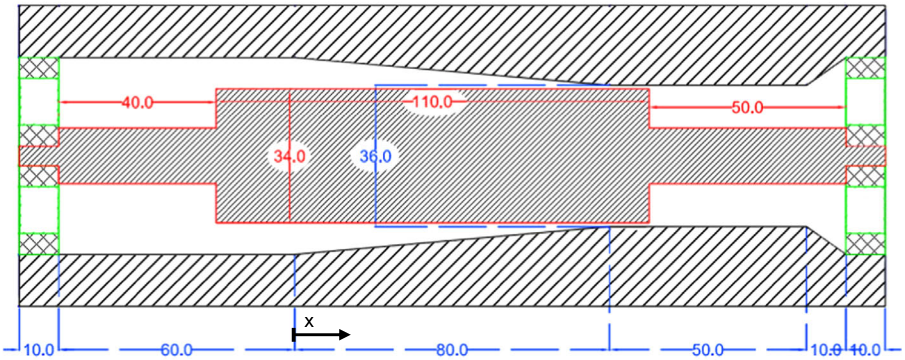

Fig. 1. Schematic of the test section of the slurry wear apparatus. All numbers designate distances in millimeters. Flow enters at left and exits at right. The axial coordinate x is measured from the beginning of the variable width annulus, which is the primary test section of the apparatus.