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Measurements and modeling of instantaneous particle orientation within abrasive air jets and implications for particle embedding

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A B S T R A C T

Previous theoretical studies indicate that the material removal mechanism and the likelihood of particle embedding in solid particle erosion processes strongly depend on instantaneous particle orientation at impact. The present study utilized pulsed laser shadowgraphy to measure the size, shape, and instantaneous orientation distributions of particles within a micro-abrasive jet at various pressures, particle sizes, and nozzle standoff distances. A particle orientation angle was defined as the angle between the particle linear velocity vector (approximately parallel to the jet centerline axis) and the line connecting the center of mass to the furthest downstream particle vertex. Particles were considered to be 'oriented', i.e. in a configuration favorable to embedding, if this angle was between 0 and 10°. The measurements revealed that, at all pressures (i) between 24% and 29.5% of the particles were oriented at the nozzle exit; (ii) the percentage of oriented particles increased slowly with standoff distance; (iii) larger particles had a stronger tendency to orient than smaller ones; (iv) particles having larger aspect ratios had a stronger tendency to aerodynamically align with the jet, and (v) although not all particles that were oriented actually embedded, the measured percentage of embedded particles on Al 6061-T6 surfaces nevertheless correlated with the percentage of oriented particles. A model capable of predicting the instantaneous particle orientation and velocity within and downstream of the nozzle was presented and shown to agree well with measurements. To the knowledge of the authors, these are the first measurements of the instantaneous orientation of abrasive particles under conditions that are typical of abrasive air jets. The results may have important implications for optimizing solid particle erosion tests and in abrasive jet machining applications.

1. Introduction

Many industrial applications involve damage due to the impingement of a jet of fast moving solid particles propelled by a fluid flow. Solid particle erosion is a complex process involving the successive impact of abrasive particles on a target that results in material removal from the target surface [1–3]. Examples of such solid particle erosion processes include erosion in dust collectors, particle transportation in pipes and channels, and abrasive jet machining processes. Erosion on brittle materials generally involves fracture and crack propagation, while ductile materials are usually eroded through cutting, plowing and chip separation mechanisms [4,5]. As shown by Hutchings [6], and Papini and coworkers [7–10], the orientation of the particles at the moment of impact can strongly affect the resulting erosion mechanism. Getu et al. [11] have shown that particle orientation may also affect the likelihood of the particles remaining embedded into the target material.

Particle embedding can be undesirable in a variety of applications. For example, it may cloud the results of solid particle erosion testing of polymers and other soft materials since the embedded particles may shield the target surface from further impacts. In the abrasive jet micro-machining (AJM) of polymer microfluidic chips, a similar mechanism reduces the etch rate [12], and also increases the surface roughness, thus affecting fluid flow [13,14]. In the AJM of micro-heat exchanger applications, the heat transfer rate may also be reduced due to the presence of embedded particles [15].

Getu et al. [11] identified two criteria for particle embedment in solid particle erosion processes: (i) that contiguous contact between the particle and the target be maintained throughout the impact, and (ii) that the magnitude of the static friction forces reach a critical value. Both of these were hypothesized to strongly depend on particle orientation, i.e. angular particles were more likely to embed when their major axis connecting the leading vertex to the center of mass aligned with the velocity vector upon impact. While the model of Getu et al. [11] predicted that certain particle orientations are more favorable to particle embedment, the particle orientations within an actual abrasive jet were not measured. The present study is thus mainly motivated by the

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unanswered question of which process parameters lead to the orientations favorable for embedding.

There are few existing analytical models capable of predicting the influence of the process parameters such as jet pressure and travel distance on the rotation of particles in an air jet. Most studies have focused on the behavior of spherical particles in a gas–solid flow, which, due to their symmetry, are simpler to analyze and measure. In these cases, the effect of parameters such as particle density and size, and the viscosity and regime of the flow on the behavior of the particles have been studied by investigators such as Marchioli et al. [16], Kuerten [17] and Kulick et al. [18]. Most actual applications, however, involve the use of irregularly shaped particles, rather than idealized spherical ones.

A number of researchers have defined parameters to describe non-spherical particle shape, in order to assess their behavior in a fluid. For example, Wadell [19] introduced a sphericity factor, Φ, defined as the ratio of the surface area of an equivalent sphere having the same volume as the actual particle, to the surface area of the actual particle. Hözler et al. [20] utilized two measures of sphericity, one in the lengthwise direction and the other in the crosswise direction, in order to relate the drag force to the orientation of particles traveling in a fluid. On the other hand, Loth et al. [21] suggested that the shape of a particle is best described by its aspect ratio.

Because of the forces and moments that act on non-spherical particles in fluid flows, their direction of motion can potentially be influenced by their orientation. Generally, the rotational motion of non-spherical particles and their likelihood of orientation with fluid flow depends on the shape of particle and the Reynolds number regime of the flow. The behavior of elongated ellipsoidal particles has been analytically studied by several investigators. Jeffery was one of the first [22], while Brenner [23,24] and Harper and Chang [25] also further developed the theoretical models. The behavior of non-spherical particles has also been studied numerically and experimentally by several investigators such as Fan and Ahmadi [26], Zhang et al. [27] and Parsheh et al. [28] during the past two decades. However, most of these investigations focused on Stokes flow in which case large aspect ratio has been found to be most likely to align with the flow direction [29]. Other Stokes flow studies such the one by Fan and Ahmadi [26] discuss the types of forces acting on a particle such as the shear induced lift. Studies in the realm of Stokes flow are useful in applications such as those describing blood flow or in the paper industry to analyze fiber flow, rather than the presently considered high speed turbulent abrasive jet flow.

Particles in a turbulent flow may exhibit quite complex behavior which is dramatically different from that in Stokes flow. In general, not only may the motion of particles be influenced by the turbulent flow, but also the characteristics of the flow may be altered by the motion of the particles. For example, depending on the flow regime and the shape of particles, non-spherical particles are often subject to an irregular or wobbling behavior in a turbulent flow [30]. This implies that the particle secondary motion may weaken the turbulent phase of the flow as a portion of their linear kinetic energy is transformed to particle rotational motion. Depending on the particle shape and size, the interaction between non-spherical particles and the flow can potentially intensify or weaken the turbulence.

Most models of the interaction between non-spherical particles and fluid flow focus on idealized disks, cylinders, long fibers and ellipsoids, for which a large variety of shapes can be described using few geometrical parameters. In their review of the literature on the behavior of non-spherical particles in high Reynold's number flows, Mando and Rosendahl [31] noted that flaky (as opposed to blocky) particles have been modeled using flat ellipsoids and disks of various aspect ratios. Depending on the regime of fluid flow and the aspect ratio, the particles may experience a preferred orientation [31]. For example, Christiansen and Barker [32] and Clift et al. [33] claim that particles above an aspect ratio of 1.7 result in significant secondary (i.e. rotational) motion. However, Zhang et al. numerically modeled the behavior of elongated ellipsoidal particles in a turbulent fluid flow, and found that only particles with an aspect ratio greater than 5 are likely to rotate and align with the flow direction [27]. Mortensen et al. [34] applied direct numerical simulation (DNS) to study the behavior of ellipsoidal particles in a turbulent flow and also reported that the tendency for alignment increases with aspect ratio. In another DNS model, Paschkewitz et al. [35] found that rigid slender fibers are most likely to be aligned. They also calculated reductions in drag (up to 26%) depending on the aspect ratio and reported that particle shape can significantly affect the turbulence. Finally, Zastawny et al. [36] used DNS to estimate the lift, drag forces and torques that act on four different non-spherical particles in a gas flow.

A major difficulty associated with modeling the secondary motion of non-spherical particles is the determination of an appropriate drag coefficient, which in general depends on both the particle shape and instantaneous alignment. While fit parameters have been used to derive drag coefficients [36], this has been done only for a limited range of particle geometries and flow regimes, and most studies ignore the influence of the instantaneous particle alignment relative to the flow direction.

Many techniques have been developed to measure particle behavior in fluid–particle flows. The earliest experimental studies of the orientation of particles appear to have been conducted by monitoring macroscopic particles in viscous fluids [37]. Later on, Salem and Fuller [38] studied the behavior of particles using an optical technique that captured the two-dimensional distribution of the small angle light scattering of particles in a flow. Bernstein et al. [29] applied a coupled system of microscopic video-photography and image analysis to determine the orientation of cylindrical particles both in laminar and turbulent water flows. They reported that the orientation of cylindrical particles was influenced by the particle rotational diffusion coefficient and flow velocity gradient. For flows more typical of abrasive jets, Ruff and Ives [39] developed a rotating double disk apparatus that applied the time of flight principle to measure the average abrasive velocity. Andrews and Horsfield [3] utilized a single-frame long exposure camera with a halogen light lamp in order to measure abrasive particle trajectory and velocity. Andrews also developed a particle correlation method that utilized an optical sensor in order to determine the distribution of sand grain velocity in a sand-blast operation [40]. Ghobeity et al. [41] applied a phase-Doppler particle analyzer (PDPA), and Dehnadfar et al. [42] utilized double-pulse laser shadowgraphy in order to measure abrasive velocity distribution. No attempt at measuring particle orientation was made in any of these studies.

In summary, although the behavior of spherical and non-spherical particles in fluids has been measured and modeled in past investigations, the studies mostly focused on Stokes flow. Very few considered flow regimes approaching those present in solid particle erosion testing and AJM applications, and none conducted measurements of instantaneous particle orientation in such flows. While previous studies have identified initial orientations of angular particles that are most likely to give rise to embedding, none considered what process parameters are likely to result in these particular orientations. The aims of this paper were to address this question, by, for the first time, measuring and modeling the distribution of instantaneous angular particle orientations in an abrasive air jet under conditions that are typical of solid particle erosion testing and abrasive jet machining applications.