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Numerical and experimental analysis of particle fracture during solid particle erosion, Part II: Effect of incident angle, velocity and abrasive size

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ABSTRACT

The accompanying paper presented and verified a numerical model to predict the fracture of silicon carbide particles impacting Al 6061-T6 aluminum alloy. In this work, further experiments under conditions that were less likely to cause fragmentation, and for a smaller particle size, confirmed the model's predictive capabilities. The model and double pulsed laser shadowgraphy were then used to study the effect of velocity, angle of attack, and particle size on particle fragmentation and rebound kinematics. The predicted percentage of incident particles that fractured was found to correlate with the average particle size after impact. Increases in both the incident particle velocity and the angle of attack were found to increase the propensity for particle fragmentation because they both increased energy transfers perpendicular to the surface. Even at the lowest considered impact angle (30°) and velocity (46 m/s), the average particle size after, compared to before impact, still decreased by 11%. A threshold incident kinetic energy perpendicular to the surface was found to exist below which no particles fractured. The average shape (roundness) of the particles changed by no more than 3.3% due to impact under all tested conditions. At a given average incident velocity, larger particles were found more likely to fracture upon impact due to their higher kinetic energy, consistent with observations from the literature. However, at a given incident kinetic energy, the numerical models predicted the smaller particles were more likely to fracture, due to an increased strain localization. Increases in the impact angle or incident velocity generally resulted in a wider range of rebound angles. The ratio of rebound to incident velocity did not depend much on velocity at a given angle, although at a given velocity, decreases in impact angle from 60° to 30° resulted in up to a 1.76 times increase in this ratio. The greater understanding of particle fragmentation provided by this study may have important applications in terms of assessing interference between incoming and rebound particles, the re-use of blasted media in blast cleaning operations, and optimizing removal rates in abrasive jet machining operations.

1. Introduction

Fracture of abrasive particles during solid particle erosion processes is an important phenomenon that may change the material removal mechanism, rebound velocity, angle and ultimately the erosion rate. This phenomenon occurs in various industrial applications such as turbomachinery [1], blast cleaning [2] and abrasive jet machining [3]. Besides providing a better understanding of why particle fracture occurs in these applications, the study of particle fracture may also have implications for the recycling of abrasives during abrasive jet machining and erosion testing [4]. Finally, there may be implications for understanding potential reduced erosion rates arising from collisions between incoming particles and rebounding fragments. The extent and likelihood of particle fracture depends on parameters such as the mechanical and geometrical characteristics of the target and particle, particle size and shape, hardness, toughness, incident velocity and angle. The accompanying paper [5] presented and verified a numerical model that was shown to be appropriate for the prediction of particle fracture in a typical solid particle erosion process. The present work provides further experimental verification of the model, while using the results to study the effect of process parameters such as particle incident velocity, angle and size on the fracture of abrasives upon impact.

Incident velocity has been found to greatly affect particle fracture in solid particle erosion [6]. For example, Salman et al. [7]

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reported that, at a relatively low incident particle velocity of less than 9 m/s, 5.15 mm alumina spheres impacting on steel target only elastically deformed, whereas at 25 m/s and above, they all fractured. They also observed that the transition from undamaged particles to fragmentation occurred suddenly at a critical velocity, and that smaller particles fractured at a higher velocity than larger ones [7]. Sparks and Hutchings [4] studied the fragmentation of 125–150 μm angular silica sand and glass spheres abrasives upon impact on silicate glass ceramic and also found that likelihood of particle fracture was strongly proportional to incident velocity. There is also empirical evidence [7,8] that the average fragment diameter decreases with increasing impact velocity, and that the fragment shape may also be influenced by velocity.

Impact angle has also been found to significantly affect the likelihood and extent of particle fracture. For example, the experiments performed by Salman et al. [7] showed that, at a constant velocity, the number of incident particles that did not fracture upon impact increased when the impact angle was shallower. They also reported that, for a given incident velocity, the number of unbroken abrasives at impact angles greater than 50° was significantly lower than below 50°. Finally, they found a higher critical value of velocity was required for onset of particle fracture at lower impact angles. However, the transition from no fracture to fragmentation of all particles occurred much faster at higher impact angles compared to the more gradual trend observed at small impact angles [7].

Abrasive size has been found to affect the likelihood of fracture at a given velocity [9,10]. Salman et al. [7] conducted various single impact experiments using 3.14, 5.15 and 7.15 mm spherical Al_2O_3 particles at incident velocities under 35 m/s and reported that the larger abrasives were more likely to fracture. They also reported that transition from full fracture to a no fragmentation mode occurred at a narrower range of velocities for larger particles than smaller ones [7]. Akbarzadeh et al. [11] studied particle fracture using 12 different types of target materials impacted by magnetite abrasives of 6.9 μm and 30.4 μm average diameters at 90 and 130 m/s incident velocity at different impact angles. They found a higher degree of fracture and fragmentation for the larger abrasives, and also hypothesized that particle size would have a greater effect on fracture at a larger impact angle.

The dependence of fragmentation on particle size is likely linked to both the instantaneous target hardness, and the apparent particle fracture toughness. For example, Kanda and Kotake have found that the specific fracture energy (energy per unit mass) required to fracture particles increases with decreasing particle size [12]. At a given incident velocity, particle fracture is also linked to particle size through changes in the kinetic energy available for creating fractures Salman et al. [7] reported that the number of unbroken particles at the same velocity is higher for softer targets. Surface hardness may instantaneously change due to the generation of an impact-induced work-hardened layer [13–15], which may depend on particle size [11,16], which, in turn may influence the likelihood of particle fracture, as discussed by Misra and Finnie [13] and Akbarzadeh et al. [11]. Particle size may also affect fragmentation due to the intrinsic differences in particle strength per unit volume. As suggested by Salman et al. [7] and Murugesh and Scattergood [8], this can be correlated to the larger number and size of flaws found in larger particles which, according to Harold [17] and Finnie [18] serve to reduce their brittle strength.

There are conflicting reports of the effect of fracture on particle shape. Sparks and Hutchings [4] collected and re-used the fragmented angular silica sand and glass spheres after multiple erosion tests on a glass–ceramic target, and found progressive fragmentation. They found that the erosion rate slightly improved while using the fractured particles after one cycle, consistent with the findings of Shipway and Hutchings [19] who found that silica particles were sharper after than before impact. However, using fragments after more than two cycles may reduce the erosion rate due to further changes in size, shape and aerodynamic condition of the fragments [4]. Others have found that abrasive fracture may also result in particle blunting that can decrease the overall erosion rate [20].

Particle fracture can influence the material removal mechanism; however, there is controversy regarding the correlation between particle fracture and erosion rate in the literature. Goodwin et al. [21] suggested that fragmentation may enhance erosion, because the piled up material (i.e., the material that is plastically deformed and extruded to the edges of the crater [22,23]) could be eroded and separated by the radial wash of fragments, and Akbarzadeh et al. reported that the secondary impact of fragments may enhance the erosion [11]. Others claim that kinetic energy consumed in particle fragmentation may not be available to erode the target, implying that the resulting erosion rate should be lower. For example, Shipway and Hutchings [19] suggested that a significant amount of impact energy was consumed in fracturing relatively brittle silica particles when impacting a boron carbide target, resulting in erosion by small scale chipping. These competing effects of particle fracture have also been used to explain the apparent plateau [6,18,24] or reduction [14] in erosion that occurs for particle sizes above ∼100–150 μm. Increased interaction between incident and rebounding particles with increasing particle size, even if it does not lead to fracture, may also lower the energy available to erode [11].

In summary, although experimental observations regarding the effect of various process and material parameters on the extent of abrasive particle fracture have been made, most existing studies were performed at a time when modern computational and experimental tools did not exist. The purpose of the present paper was to use state-of-the-art double-pulsed laser shadowgraphic measurements and computational models in order to rigorously investigate the influence of process parameters such as particle size, incident velocity, impact angle and kinetic energy on the propensity for particle fracture, the size and shape of fragments, and the fragment rebound kinematics.

2. Experiments

In order to analyze the influence of incident velocity, impact angle, and particle size on the extent of abrasive fracture, and to further experimentally verify a numerical model, air jet impact experiments further to those presented in Ref. [5], were performed using a commercial micro-blaster (Accuflo, Comco Inc., Burbank, CA, USA) (Table 1). In all cases, double-pulsed laser shadowgraphy [5] was used to measure rebound particle velocities and angles, and the distributions of size and shape of collected abrasive

Table 1
Process parameters using in shadowgraphy experiments. The last column indicates whether numerical models were also developed for a particular set of parameters. *Data in last row from accompanying paper [5].

Grit size	Pressure (kPa)	Average velocity (m/s)	Impact angles (deg)	Standoff distance (mm)	Numerical modeled
120	160	100.1	60	20	YES
60	100	46	30	20	YES
60	100	46	60	20	NO
60	400	100.3	30	20	NO
60	400	100.3	60	20	YES*

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