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Numerical modeling of particle embedment during solid particle erosion of ductile materials

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ABSTRACT

Particle embedment may occur in erosion testing, abrasive jet machining, blast cleaning and other industrial processes in which high speed impact of particles on relatively ductile targets occurs. It may strongly affect erosion rates, and lead to undesirable changes in surface roughness. Three-dimensional smoothed particle hydrodynamics (SPH) simulations were used to simulate particle embedment when 219.2 μm and 362.9 μm angular silicon carbide particles impacted a strain and strain rate hardening 6061-T6 aluminum alloy target under various process conditions. The models were assessed by comparison with measured embedment. Analysis of the results showed the following: (i) once the value of the effective friction coefficient between the substrate and the abrasive was determined by comparing predicted and measured embedment at one set of process conditions (particle velocity, size, angle of attack), the same friction coefficient could be used in models of all other combinations of process conditions to correctly predict embedment. (ii) Consistent with a previous simplified rigid-plastic analysis of idealized rhomboid particles impacting a polymer target, the static frictional force occurring after the maximum depth has been reached, the particle orientation and the impact angle all strongly affected embedment. Unlike the previous simplified model, the present model considered local strain rate and strain hardening, making it applicable for ductile metal targets. (iii) Consistent with some, but not all, reports in the literature, embedment at a given velocity increased with particle size. (iv) For a given particle size, embedment increased with incident velocity. (v) A critical minimum velocity below which embedment would not occur was predicted. The trends were discussed in terms of embedment mechanisms and particle impact kinematics. Overall, the work demonstrates that SPH methods can be used to provide insight into complex solid particle erosion phenomena.

1. Introduction

Solid particle erosion involves the successive impact between particles and a surface that results in material removal [1–4]. It occurs in a wide variety of industrial processes including, amongst many others, abrasive jet machining, surface polishing, blast cleaning, and the erosion of gas pipelines and turbo machinery. When the particles impact relatively ductile surfaces, the potential for particle embedment exists, and this may greatly affect the resulting material removal rate and surface quality. For example, in operations that utilize abrasive jets to purposefully remove target material such as in abrasive air, slurry and water jet micro-machining, embedded abrasives may reduce the erosion rate [5], negatively impact the heat transfer rate in abrasive jet micro-machined heat exchangers, and increase the roughness, thus affecting the flow in micro-machined microfluidic devices [6,7].

There have been a number of experimental works aimed at determining the parameters that affect particle embedment. These studies are sometimes contradictory. For example, for a limited range of sizes, Getu et al. [8] reported that particle size did not have a significant influence on particle embedment, while Day et al. [9] and Hadavi et al. [10] found that particle embedment increased with particle size. Getu et al. [8] also reported the existence of a minimum impact velocity required for particle embedment.

Temperature can significantly influence the mechanical properties and behavior of several types of materials (e.g., polymers) [11–15], and therefore may also influence embedding. Getu et al. [15] conducted extensive investigations on the cryogenic abrasive jet micro-machining of polymers and found that, at all angles of attack and for all the tested materials, the amount of particle embedding was significantly reduced.

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Particle impact angle and velocity also have important roles in the embedment of particles. Getu et al. [8] reported that the target area covered by embedded particles decreased when blasting at oblique impact angles [8]. They also observed that the minimum velocities that caused embedding occurred when the particle was oriented such that the incident velocity vector was aligned with the major axis of the particle [8,10]. This is most likely because such a configuration reduces the probability of rebound rotational energy being induced during the impact, as also noted by Papini and Spelt [16].

A number of investigators have identified an equilibrium phase when the number of embedded particles reaches a plateau. For instance, Getu et al. [8,15] reported that the number of embedded Al_2O_3 particles in polymer targets increased with increasing particle dose, until a critical dose had been reached. This is in agreement with Wu et al. [17], who observed that aluminum alloy specimens initially gained mass due to embedment of SiC and Al_2O_3 abrasives, and that a steady state was achieved only after long transients. Chen et al. [18] found a similar phenomenon when observing Al_2O_3 particle embedment into Hastelloy X. Zu et al. [19] also reported the presence of embedded silica abrasives in a pure aluminum target. The steady state likely occurs when the rate of particle embedment reaches that of material removal [20].

The criteria for embedment of spherical and angular particles appears to be different [8]. Walley and Field [21], analyzed spherical particle impact craters and hypothesized that embedment occurs when a particle penetrates sufficiently to be surrounded by deformed material, preventing the elastic rebound forces from it. This is consistent with the work of Getu et al. [8], who reported that spherical particle embedment is a function of maximum penetration depth, which depends on the dynamic friction on the incident penetration trajectory. For angular particles, Getu et al. [8] suggested that the embedding criterion was more complex, depending more on the static friction at maximum penetration.

The present work aims to predict embedment of realistically-shaped angular particles into a relatively ductile metal target. In pioneering work with flat square plates, Hutchings [22] determined that initial particle orientation can strongly influence the erosion mechanisms of a ductile material, and developed a rigid-plastic model to predict the trajectory of such plates during impact. Getu et al. [8] utilized similar principles in developing the only existing angular particle embedment model, hypothesizing that impacting idealized rhomboid-shaped angular particles would embed into an elastic, perfectly plastic polymeric material if two basic criteria were met. The first criterion was that the particle trajectory during impact would be such that a contiguous surface contact between the target and abrasive would be maintained during the impact, and the second was that the friction force that tended to keep the particle embedded would be larger than the elastic rebound force. Getu et al. [8] used a two-dimensional rigid-plastic target material model that assumed a constant contact pressure, in order to predict the trajectory of idealized rhomboid particles as they impacted, and thus whether contiguous contact was maintained. For cases where it did, they used an elastic rebound model and found that regardless of particle size and impact angle, the static friction coefficient remained approximately constant for a given particle-target system [8]. Despite its usefulness in providing a baseline to understand embedment, the model is inappropriate for use on metallic materials that strain and strain rate harden. Furthermore, rigid-plastic models cannot predict thermal softening, crater edge pile-up, and other phenomena such as non-uniform contact stresses that may affect particle kinematics and embedment.

Numerical methods can be used to address some of the shortcomings of rigid-plastic models in the analysis of solid particle erosion. Most previous finite element (FE) models utilized spherical particles that, compared to angular particles, induce a relatively small degree of plastic deformation into the target. For instance, Junkar et al. [23] applied FE to simulate the impact between single spherical particles and a substrate in water jet machining and predicted the crater depth. Shimizu et al. [24,25] used a plain-strain approximated FE model to investigate material removal rate and distribution of plastic strain in the extruded material in the front of an impacting spherical particle in mild steel, ferritic and spherical-graphite cast iron. El Tobgy and Elbestawi [26] developed FE models for the impact of spherical particles on Ti–6Al–4V alloy substrate and studied the effect of particle size and incident angle and velocity on removed material. They reported that steady state was achieved after 3 impacts and found their models to be in fair agreement with the analytical models of Finnie [27], Bitter [28] and Hashish [29]. Wang and Yang [30] used a Lagrangian FE technique to study the influence of incident angle and velocity on the erosion rate resulting from the impact of spherical particles on a Ti–6Al–4V alloy surface, and reported reasonable agreement with experiments performed using angular particles [31].

In reality, most solid particle erosion problems involve the impingement of angular particles that leave much larger amounts of plastic deformation on the substrate. Takaffoli and Papini [32] reported that distortion of finite elements in FE modeling of angular particle impacts resulted in inaccurate calculation of strain and stress and increased the computational time dramatically. They also reported that adaptive re-meshing and element deletion techniques could limit element distortion, but at the penalty of a large computational cost, or a large inaccuracy, respectively.

Mesh-free methods such as smoothed particle hydrodynamics (SPH) utilize particles to represent the computational domain that are not connected together, and therefore large deformation problems can be dealt with more effectively [33]. Takaffoli and Papini [34–36] recently demonstrated that SPH methods can be used to successfully model single and multiple angular particle impacts in the erosion of metal targets by aluminum oxide particles. Their models utilized realistically-shaped particles and considered strain and strain rate hardening, and were thus able to accurately predict measured particle kinematics, crater dimensions, material removal, and pile-up height. They did not, however, consider particle embedment in their models. They focused on dynamic frictional forces affecting the incident trajectory, rather than static ones affecting rebound or embedment.

In summary, there is currently no model that can be used to study the embedment of realistic particles into ductile metal targets. The only existing model, that of Getu et al. [8] for rhomboid particle impact on perfectly plastic polymers, revealed some fundamental aspects of the embedment process. However, it is unsuitable for detailed study of the embedment of more realistic particle geometries on strain and strain rate hardening metals. The aim of the present work was to determine whether SPH could be used with appropriate constitutive models and realistic angular particle geometries to predict embedment in such materials, and to shed more light on the effect of process parameters on the likelihood of embedment.

2. Experiments

2.1. Measurement of particle embedment

Experiments were conducted to determine percentage embedment, i.e. the percentage of the total number of impacting particles that remained embedded. Al 6061-T6 (90 BHN) targets were impacted by short bursts of grit 90 and grit 60 angular silicon carbide (SiC) abrasive, whose distribution of planar area,