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Modeling, simulation, and analysis of the impact(s) of single angular-type particles on ductile surfaces using smoothed particle hydrodynamics

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ABSTRACT

Modeling the impact of single angular particles contributes to an understanding of the fundamental mechanisms of erosive wear. However, most previous studies focus on well-defined symmetrical particles, which are not representative of abrasive particles. Hence, this study develops a mesh-free model based on smoothed particle hydrodynamics to simulate the impact(s) of arbitrarily shaped particles on ductile material. These particles are modeled as polygonal rigid bodies by measuring the corner vertices. Oxygen-free high thermal conductivity copper is selected as the target material. The ductile material properties are modeled using the Mie–Grüneisen equation of state and the Johnson–Cook model. In order to investigate the erosion dependency of angular-type particles on the initial orientation, simulations are performed by varying the initial input conditions and using different types of angular particles. Common deformation mechanisms such as cutting, machining, ploughing, and prying-off are successfully reproduced by the model. The initial orientation is found to influence the erosion mechanism through three shape-related parameters, namely the rake angle, centroid offset angle, and angularity of the impacting vertex. In particular, the rake angle significantly influences the erosion mechanism through particle rotation, although this effect decreases as the angularity increases. The centroid offset angle additionally changes the position of the critical rake angle, producing an opposite effect on the backward and forward impact. For irregularly shaped particles, the complexity is reflected in the irregular relationship between kinetic energy loss and the initial orientation of the particle; the variation in the rebound angle exhibits a similar trend to the kinetic energy loss.

1. Introduction

Studies on the impingement of single angular particles of known geometry are very helpful in understanding the fundamental mechanism of material removal in erosive wear. For example, through experimental and theoretical studies of single square particles (8 mm), Hutchings [1] identified two types of cutting deformations: Type-1 cutting (see Fig. 1(a)) and Type-2 cutting (machining) (see Fig. 1(c)). Papini et al. observed that a rhombic particle (6.36 mm) with backward spin can lead to a “prying-off” action (see Fig. 1(d)), which is different from the machining action of square particles [2,3]. Winter and Hutchings [4] revealed that angular-type particles at largely negative rake angles, could result in ploughing deformation (see Fig. 1(b)); ploughing is generally accepted as the method by which spherical particles remove material [5].

Single-particle experiments [3,7,12,13] have played an important role in studies on the erosion mechanism of angular particles, with contributions from theoretical studies and computer models. Theoretical studies by Finnie [14,15], though simplified, form the basis for subsequent studies. Subsequently, computer models combined with single-particle experiments became a popular way of conducting such research. Hutchings [1] first discussed the relationship between the rake angle, rotation of particles (forward or backward), and cutting deformation through experimental observation. Moreover, the crater profile and the particle trajectories were predicted by a rigid-plastic model, resulting in a better understanding of the influence of particle rotation. The rigid-plastic model was recently improved by considering the friction coefficient and nonuniform contact area [9]. This improved model has been verified through an experiment conducted on single rhombic particles (6.36 mm) impacting on aluminum targets over a wide range of incident parameters [2,3], including various initial orientations and impact angles. The observed phenomena for square particles ($A=90^\circ$) agree with previous data by Hutchings [1], and new phenomena were observed by using sharper angular particles ($A=60^\circ$ and $A=40^\circ$).

However, most previous studies have focused on well-defined symmetrical particles, such as square particles [1,6] and rhombic particles [3,7,8], as shown in Fig. 2. One reason for this is that symmetrical particles are relatively easy to control in experiments. Nevertheless, computer models are not subject to this limitation. The rigid-plastic

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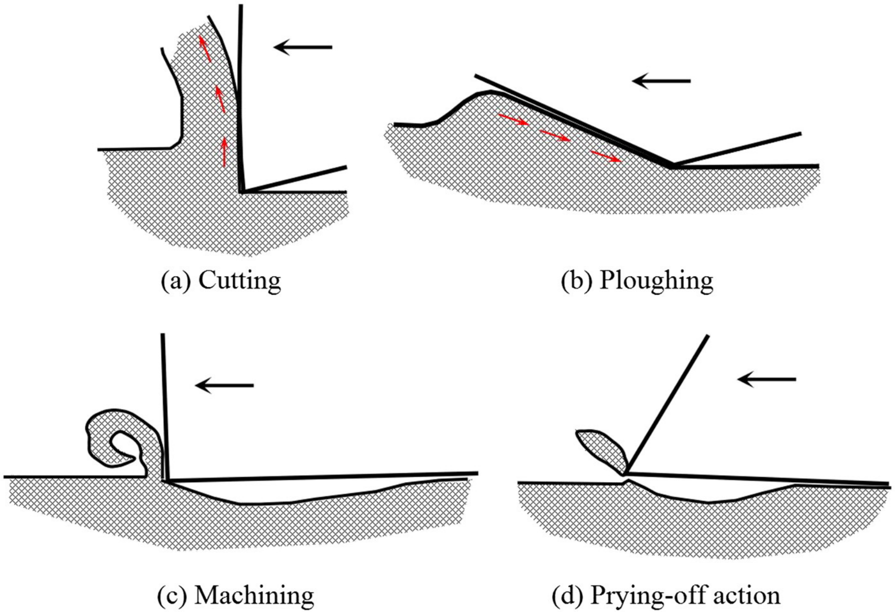
(a) Cutting (b) Ploughing

(c) Machining (d) Prying-off action

Fig. 1. Material removal mechanisms due to impact of single angular particle.

model developed by Papini and Spelt [9] is able to handle arbitrarily shaped particles, but no relevant studies have been reported. Papini [10] proposed a mesh-free erosion model wherein irregularly shaped particles were modeled as polyhedra according to the size and shape distribution of abrasive powder. Papini's model was applied to simulate multiple and overlapping impacts by various particles with uniform incident parameters such as impact velocity and impact angle [11], but more specific parameters for individual particles (such as rake angle) were not considered. Hence, Papini's model resembles a macroscopic model for predicting the erosion rate rather than investigating the fundamental mechanisms of erosion. Therefore, the present study considers single particles with arbitrary shapes and investigates their impact characteristics, including the particle kinematics and deformation mechanism.

Computer models based on rigid-plastic theory have inherent shortcomings, as they fail to consider complex constitutive relations, neglect the effect of elastic spring back, and require tuning to obtain results that are consistent with measured data. In recent decades, numerical models based on the finite element method (FEM) and smoothed particle hydrodynamics (SPH) have increasingly been used in the study of erosive wear [17,18,19,20] and similar fields (*e.g.* shot peening [21,22]). Papini applied FEM to simulate the impact of a single rhombic particle on a copper target [7]. The model successfully reproduced typical mechanisms or behaviors arising due to the impact of angular-type particles, such as cutting, extruding, and chip separation. Using the Johnson–Cook plasticity model, the predicted crater profiles are consistent with measured data. Azimian employed a similar FEM model to investigate the effect of incident parameters on the rebound kinematics and erosive craters [23]. However, large deformations due to the impact of angular particles may lead to a mesh distortion problem [6], which is not conducive to the stability of FEM. As a result, FEM is unsuitable for multiple and overlapping impacts. Hence, the SPH approach, which is a mesh-free method, has become more popular in recent years. Relevant applications include the simulation of single-particle impacts [6,8,24], particle embedment [25], and multiple and overlapping impacts [10,11]. Hence, in this study, an erosion model based on SPH is developed to study the erosion caused by the impact of irregularly shaped particles.

The parameters that influence the erosion process can be divided into two categories. The first type is flow-related parameters such as the impact velocity and impact angle; the second type is microscopic parameters from the view point of an individual particle, such as the initial orientation. An irregularly shaped particle with an arbitrary orientation may impinge on the surface. Hence, at the moment of impact, the rake angle, impacting vertex, and position of the center of mass depend on the actual orientation of the particle. To quantify the interactive influences of these parameters, a variable that can reflect the erosion damage is required. The kinetic energy loss of the particle is a good option.

The remainder of this paper is organised as follows. In Section 2, the SPH erosion model is introduced, and the procedure of modeling an arbitrarily shaped particle is discussed. Section 3 describes the application of this model to simulate the impact of single angular-type particles on

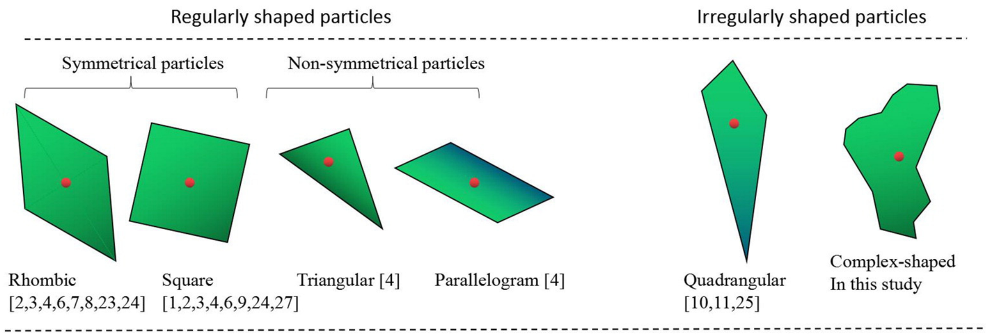

Fig. 2. Single angular-type particles used in previous studies.