Wear 313 (2014) 135–142

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

A numerical study on the effect of particle shape on the erosion of ductile materials

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ARTICLE INFO

Article history:
Received 4 December 2013
Received in revised form
10 March 2014
Accepted 11 March 2014
Available online 18 March 2014

Keywords:
Erosion rate
Shape effect
Ductile material
Finite element analysis

ABSTRACT

Although extensive studies have been performed to establish the relationship between material erosion rate and system parameters, how to accurately predict the erosion rate of engineering materials is still a challenge. Recent experiments have shown that particle shape cannot only affect erosion rate but also change material erosion mechanisms, thus casting doubts on existing models based on the erosion mechanisms incurred by ideal rigid spherical particles. In this study, finite element simulations with the Johnson–Cook constitutive and failure models are used to study the erosion mechanism and erosion rate of different materials under the impact of solid particles with different shapes. The simulations not only reveal distinct mechanisms under the impact of particles with different shapes, but also establish the relationship between the erosion rate and particle shape. Importantly, the established relationship is in good agreement with existing experimental observations. The present work not only gains interesting insights into the effect of particle shape on material erosion, but also provides useful guideline for developing anti-erosion strategies.

1. Introduction

Erosion is one of the major failure modes that can cause fatal damage to components in offshore equipment, such as gas turbine, oil and gas pipeline, drilling platforms, etc. In an erosion process, solid particles are entrained into fluid flow in an operating process, and impact on a component surface to cause local damage. This damage mode affects not only operating productivity, but also operating safety as well. Therefore, it is highly desirable to find out a robust and accurate method to predict the erosion for offshore equipment.

To analyze the erosion damage and estimate the lifetime of equipment in service, great efforts have been made to understand the effect of operating parameters, such as shot impact angle and velocity on erosion processes [1–9]. For example, Yerramareddy and Bahadur [5] studied the erosion behavior of Ti–6Al–4V alloy under ambient conditions using a sand-blast type test rig and silicon carbide particles. Their experiment exhibited a typical ductile erosion pattern with the maximum erosion occurring at an impact angle of 30°. Oka et al. [6–9] performed systematic experimental tests to study the erosion damage caused by the impact of solid particles and the effect of the ratio of cutting action vs. repeated plastic deformation on material removal. Their experiment work revealed the importance of both material properties and particle impact angle. Undoubtedly, those previous experiments provided important guidance for developing empirical or semi-empirical models to describe erosion processes. Two of the most widely used models are the Finnie and Bitter's models [1–3]. However, these models can only match with experiment for ductile materials under low impact angles, where material cutting is the dominant mechanism [4]. Many researchers tried to improve the Finnie and Bitter's models, or propose new models. But all these models are only applicable to specific materials, erosion particles and operating conditions. So far only limited success was achieved to develop a generalized model for material erosion [4–9].

In general, it is both time consuming and labor intensive to study the erosion process experimentally. Since the 1990s, computational methods, such as a finite element (FE) method, have been used to study materials erosion behavior. Initially, two-dimensional (2D) models were used to investigate system parameters that affect material erosion [10,11]. However, since 2D models cannot correctly consider the effects of multiple impacts and impact area overlapping, therefore three-dimensional (3D) FE models have been used subsequently for erosion modeling. For example, Alman et al. [12] studied erosion behavior of both brittle and ductile materials, and concluded that the impact angle was an important factor that affects erosion rate. They also showed that

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http://dx.doi.org/10.1016/j.wear.2014.03.005
0043-1648/

the ductile material exhibits the maximum erosion rate at an impact angle of about 20–40°. ElTobgy et al. [13] studied the erosion process using multiple impacts, and reported that a single particle impact is insufficient, and multiple particles are needed to create erosion damage. Wang and Yang [14,15] performed FE simulations on erosion with 100 spherical particles and analyzed the erosion rate of both ductile and brittle materials. It should be noted that all of these simulation models were based on the erosion mechanism incurred by ideal rigid spherical particles. However, recent experimental results revealed that the erosion mechanism can be different for different shapes of particles [6–9]. Hence, it is interesting to perform simulations with multiple impacts using different particle shapes to study the erosion mechanism and erosion rate.

In this study, we perform 3D FE simulations using the Johnson–Cook material model and also Johnson–Cook failure model to study the effect of particle shape on the erosion rate and erosion mechanism. Three different ductile materials are tested by multiple impacts using both spherical and non-spherical particles. The obtained simulation results are also compared with published experimental data.

2. Simulation model and numerical method

2.1. Simulation settings

In ductile materials, it is known that erosion can occur via the following two mechanisms, i.e., repeated plastic deformation and cutting action. Thus, the total erosion is a combined contribution from both mechanisms [16–19]. It was also shown that the particle angularity plays an important role in erosion. However, the underlying mechanism and its effect on erosion are still unclear. Previous numerical studies [13–15] have shown that models based on single particle impact are insufficient to describe erosion behavior. As a result, multiple particle impacts are required to consider overlapping and accumulative damage. Therefore, in the present work, we perform 3D FEM simulations to consider both multiple particle impacts and particle angularity effect.

Schematic of the present model is shown in Fig. 1. Different particle parcels, for example, spherical particles, cubic particles, mixed spherical and cubic particles, etc., are used in order to study angularity effect. In each parcel, 100 particles are used. To save the simulation times, these 100 particles are divided into 10 groups. In each group, 10 particles are directed to impact the substrate surface simultaneously with random impact locations.

Practically, the erosion process of a target material is often characterized by erosion rate. However, there are several ways to define erosion rate. Here, we follow the definition in [15], in which the erosion rate is defined as the ratio of the cumulative mass loss of the target material to the total particle weight, that is,

$$\text{Erosion rate} = \frac{\text{cumulative mass loss of substrate material}}{\text{impact particles weight}} \tag{1}$$

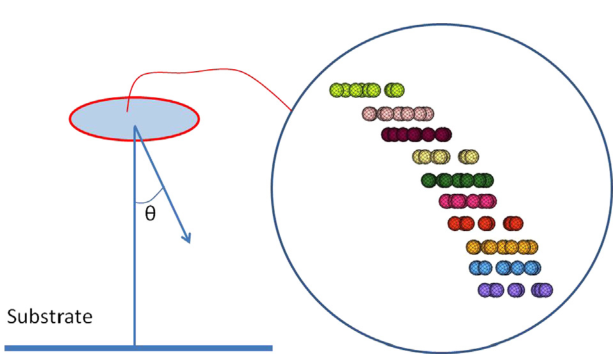

Fig. 1. Side view of particle parcel. The particles are simulated by 10 layers.

2.2. Mechanical models

A key issue in the simulations is the choice of material models to consider elasticity, plasticity, damage initiation and propagation. In this study, the elastic response of the target material is assumed to be linear and is defined by elastic modulus and Poisson's ratio. The plasticity model and failure model are briefly described below.

2.2.1. Plasticity model

The Johnson–Cook (J–C) visco-plastic model is used in this study [20,21]. In this model, the flow stress $\overline{\varepsilon}$ depends on the equivalent plastic strain ($\overline{\varepsilon}$), equivalent plastic strain rate ($\dot{\overline{\varepsilon}}$), and temperature. The model can be expressed as follows:

$$\overline{\sigma} = (A + B\overline{\varepsilon}^n)\left(1 + C\ln\left(\frac{\dot{\overline{\varepsilon}}}{\dot{\overline{\varepsilon}}_0}\right)\right)(1 - T^{*m}) \tag{2}$$

where A, B, C and m are material constants, n is strain hardening exponent, $\dot{\overline{\varepsilon}}/\dot{\overline{\varepsilon}}_0$ is the normalized equivalent plastic strain rate (typically normalized by a strain rate of 1.0 s^{-1}), and T^* is the homologous temperature, which is defined as follows:

$$T^* = \frac{T - T_r}{T_m - T_r} \tag{3}$$

where T is the current temperature, T_r is the reference temperature, T_m is the melting temperature of material. It is assumed that the strength is isotropic.

2.2.2. Failure model

The Johnson–Cook failure model is used for the ductile failure criterion [20,21] in which the equivalent plastic strain at the onset of damage, $\overline{\varepsilon}_D^{pl}$, is assumed to be a function of stress triaxiality (η), strain rate ($\overline{\varepsilon}^*$) and temperature. The Johnson–Cook failure model is expressed in term of the failure strain as follows:

$$\overline{\varepsilon}_D^{pl} = [d_1 + d_2\exp(-d_3\eta)](1 + d_4\ln\overline{\varepsilon}^*)(1 + d_5T^*), \eta = \frac{\Sigma_h}{\Sigma_e}, \tag{4}$$

where, d_1– d_5 are material constants, Σ_h is the hydrostatic stress (positive in tension), Σ_e is the von-Mises stress, and T^* is the homologous temperature.

In the explicit FE method, the overall damage variable D captures the combined effects of all active damage mechanisms, and is computed in terms of the individual damage variables. The damage parameter D is defined as follows:

$$D = \frac{\sum \Delta\varepsilon^{pl}}{\overline{\varepsilon}_D^{pl}} \tag{5}$$

In each increment, $(\Delta\varepsilon^{pl})_i$ is calculated for finite element i, and the damage parameter D for element i is subsequently calculated. When the damage parameter D reaches 1, the element i is deemed to have lost its loading capacity and thus removed from the model instantly [15].

In this study, three different materials, that is, stainless steel, aluminum alloy Al6061-T6 and titanium alloy Ti–6Al–4V, are used in the simulations, and the simulation results are compared with published experimental data. Summary of their material properties is presented in Table 1 [5–9,20,21].