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Finite element analysis of multiple solid particles erosion in cermet coating

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ABSTRACT

In this paper, an improved three-dimensional (3D) numerical model for erosion process was developed in which multiple solid particles were adopted for characterizing the accumulation of damage. In this model, the metal-ceramic composite materials were coated on nickel-base superalloy. The explicit solver LS-DYNA has been used to simulate the erosion process. The effects of the coating thickness, particle size and impingement velocity on the stress distribution and damage of the target material were studied. The simulation results show that the reasonable coating thickness can effectively prevent its peeling. With the increase of impact velocity, radial and lateral cracks are initiating and propagating on the coating surface. Particle size has the significant influence on the coating loss. This multiple particle model can help understanding and predicting the erosion results better than conventional FE simulations.

1. Introduction

Solid particle erosion prevails in many industries such as aerospace, power generation, coal mining, as well as in manufactured goods like gas turbines, rocket nozzles, and boiler tubes, which caused great economic losses [1]. The flue gas turbine is one of the important energy-saving equipments in petrochemical enterprise. Currently, it is an effective energy recovery in related fields at home and abroad. However, the crushing catalyst powder of high-temperature flue gas can cause serious erosion wear to the turbine blades [2]. The erosion will shorten service life of flue gas turbine. On the other hand, constant maintenance and some unforeseeable outages can lead to great economic losses. With the development of surface engineering, the application of protective coatings appears to be the most effective option to date [3]. However, the erosion mechanisms of coating materials are still not clear.

The subject of erosion has been extensively considered in theoretical basis and experiment investigation since at least the 1970s. Valuable insights have been obtained particularly from the work of Finnie [4], Hutchings [5], Bitter [6], Evans [7], Lawn and Swin [8], and Sundararajan and Roy [9], just to cite a few. Empiricism has absolute predominance in the process of predicting material erosion. Moreover, experimental techniques is costly, time consuming, and difficult. Numerical and finite element models can be used as a time and cost effective tool and have also been developed and applied with some success [10–12].

Previous FE methods have tended to concentrate on single particle impacts [13,14], using axisymmetric two-dimensional models for computational efficiency. However, the impacting coverage and intensity were not sufficiently applied to the FE analyses for the single particle impacts. In recent years, great progress has been made in modeling. Naresh Kumar [15] developed a FE of multi-particle impact on erosion in abrasive water jet machining of titanium alloy. Thus, the calculation did not involve the target containing coating. Griffin et al. [16] studied erosion caused by the five particle impingement using a three-dimensional dynamic analysis within ABAQUS/Explicit on alumina scale/MA956 substrate. However, their study did not take the effects of an interphase into consideration. Moreover, a single-layer coating is not enough comprehensive. Repeated impacts focus on a single point, which will reduce erosion coverage. In addition, real erosion factors have not fully considered, such as plastic deformation and rotation of the particles. Erosion mechanisms still have many problems to be solved.

This paper is to develop a finite element model that can better characterize the erosion process. A 3D finite element model with multiple solid particle impacting an cermet coating with nickel-base superalloy is developed to simulate erosion behavior using explicit solver LS-DYNA. With this model, the effect of particle size, erodent velocity and coating thickness are studied in details. The results provide a useful mean for guiding the choices of the optimal coating parameters.

2. Finite element simulation of erosion progress

2.1. Explicit finite element algorithm

Due to the fact that the impact takes place for a very short time, an implicit code could not be applied. The transient dynamic behavior is modeled using the explicit dynamic analysis available at the finite

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element-based commercial code ANSYS/LS-DYNA, which is an explicit numerical code, popularly used to analyze a variety of impact problems [17,18].

The analysis employed a Lagrangian formulation. The momentum equation is expressed as Eq. (1).

$$M\ddot{U} = F^{\text{ext}} - F^{\text{int}} \tag{1}$$

where M is the lumped mass matrix, $\ddot{U}$ is the nodal acceleration at each time step, F^{ext} is the externally applied load at each node, and F^{int} is the internal force. This set of equations is solved by the central difference method using an explicit time integration scheme and employing a lumped mass matrix.

To advance to time t^{n+1}, central difference time integration is usually used as follows:

$$\ddot{U} = M^{-1}\left(F^{\text{ext}} - F^{\text{int}}\right) \tag{2}$$

$$\dot{U}^{n+1/2} = \dot{U}^{n-1/2} + \ddot{U}^{n}\Delta t^{n} \tag{3}$$

$$U^{n+1} = U^{n} + \dot{U}^{n+1/2}\Delta t^{n+1/2} \tag{4}$$

where $\Delta t^{n+1/2} = \frac{(\Delta t^{n} + \Delta t^{n+1})}{2}$, and $\dot{U}$ and U are the global velocity and displacement vectors, respectively. Δt is the time step. Increment number is denoted by superscript (n); $n - 1/2$ and $n + 1/2$ refer to mid-increment before and after step n. Then, update the geometry by adding the displacement increments to the initial geometry:

$$X^{n+1} = X^{0} + U^{n+1} \tag{5}$$

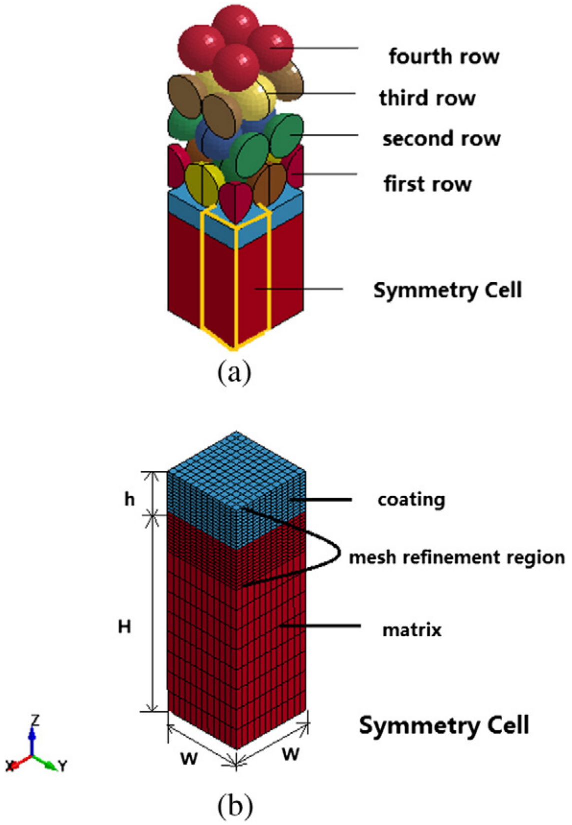

Fig. 1. FE model of multiple impingement of multiple particles: (a) full model, (b) discretized symmetry cell.

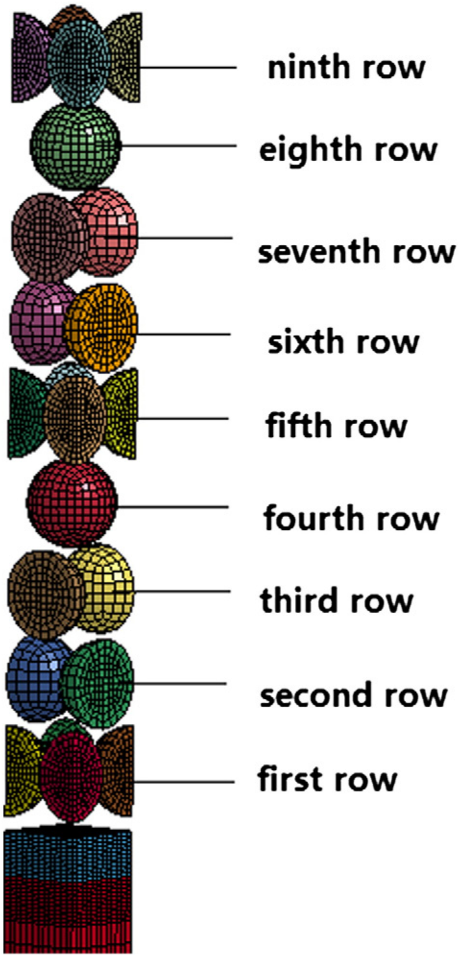

Fig. 2. Multiple particles model.

where X is the geometric configuration coordinates, and X^0 is the initial geometric configuration coordinates. We have found that vector the results are much less sensitive to round-off error, although more storage is required to store the displacement.

2.2. Modeling assumption

The restrictive assumptions have been used to derive erosion models due to the complexity of the erosion process. In view of the blade working environment, the paper makes the following assumptions:

(1) The flue gas turbine is always in the same working condition.
(2) The particles are considered rigid spheres of uniform radius.
(3) Blade erosion damage formed by the particles at different positions are independent of each other.
(4) The erosion is supposed impinging the target surface at impact angle $\alpha = 90^\circ$.This paper does not consider the influence of erosion angle.

Table 1
Material constants of the coating material.

Material properties	Symbol	Cr_3C_2/NiCr
Density	ρ (g/cm^3)	2.36
Poisson's ratio	μ	0.3
Young's modulus	E (GPa)	210
Yield stress	σ_y (MPa)	900
Tangential modulus	E_t (MPa)	650