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Numerical study of impact erosion of multiple solid particle

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ABSTRACT

Material erosion caused by continuous particle impingement during hydraulic fracturing results in significant economic loss and increased production risks. The erosion process is complex and has not been clearly explained through physical experiments. To address this problem, a multiple particle model in a 3D configuration was proposed to investigate the dynamic erosion process. This approach can significantly reduce experiment costs. The numerical model considered material damping and elastic-plastic material behavior of target material. The effects of impact parameters on erosion characteristics, such as plastic deformation, contact time, and energy loss rate, were investigated. Based on comprehensive studies, the dynamic erosion mechanism and geometry evolution of eroded crater was obtained. These findings can provide a detailed erosion process of target material and insights into the material erosion caused by multiple particle impingement.

1. Introduction

Erosion wear caused by the impacts of particles is one of the most common harmful behaviors of equipment in the multiphase flow [1–3]. The development of unconventional oil and gas resources with low permeability increased in recent years with the consumption of conventional resources. Hydraulic fracturing technology with high flow rate and high sand ratio is crucial to the development of low-permeability or extra low-permeability reservoirs [4–6]. Erosion wear due to proppant impingement is one of the most important issues in the fracturing process. Pipeline pressure, which reaches up to tens to hundreds of MPa, create cracks for downhole formation. Unpredictable consequences would occur if the conveying pipelines suffer from erosion failure. Proppant in the fracturing fluid affects tool surface and causes erosion scars and cracks, which severely affect production safety [7–9]. Thus, the erosion mechanism of substrate material or deposited coating under fracturing working conditions should be urgently studied [10–12].

Considerable research investigated erosion wear [13–15]. Erosion is a complex problem caused by many factors, such as particle velocity, impact angle, particle shape, and particle size [16,17]. Various experiments were conducted to explain the erosion process. Experiments usually provide limited information, such as erosion rate and eroded morphologies. These limited data cannot provide sufficient information to further analyze the dynamic erosion process. Numerous experiments that aim to study the influence of each factor on the erosion mechanisms experimentally consume substantial time and money. In addition, the dynamic impact process occurs briefly; thus, capturing the erosion behavior of an erodent and a target material is a difficult process. Some researchers used high-speed cameras to capture images during particle impingement and studied its dynamic characteristics. However, expensive and sophisticated instruments are needed, which substantially increases testing cost. However, numerical technique allows researchers to model the erosion process with different parameters. The numerical model can provide detailed information of the particle and target material, such as stresses, interaction forces, and deformation [18–21]. The numerical values need to adjusted and recalculated to investigate the effect of different parameters on the dynamic process. Hence, the effects of these parameters on the erosion characteristics can be investigated.

Some researchers studied erosion wear caused by abrasive particle collisions [22–24]. Aponte et al. used computational fluid dynamics to predict the erosion behavior of geometries in a fluid environment that contains abrasive particles [25]. Liu et al. studied the erosion of pipeline caused by sand particles in the oil and gas transportation system [26]. In their studies, the computational fluid dynamics helped provide insight into the movement of particle and fracturing fluid and predict erosion rate. However, the interactions between the particle and target material cannot be considered, which is the core issue of erosion wear mechanism. The continuous impingement between the particles and target material causes severe erosion. To address this problem, the present study proposes a multiple particle impact model to solve the dynamic erosion pro-

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Table 1
Mechanical material properties.

Material	Density (kg/m^3)	Young's modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Poisson's ratio
Q345	7850	210	345	490	0.28

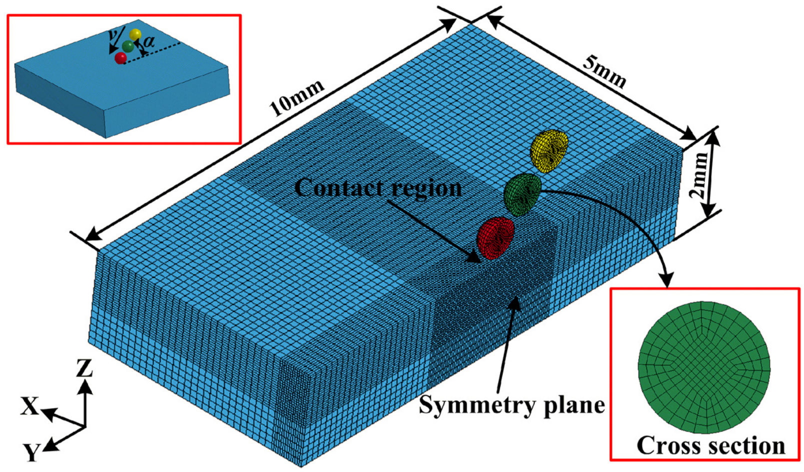

Fig 1. Mesh generation of the multiple particle impact model.

cess. The effect of impact parameters on erosion characteristics was investigated. Detailed change information of target material under multiple particles impingement was obtained for further analyses. The numerical results of the dynamic erosion process would help explain the erosion mechanism and provide scientific basis for material erosion due to multiple particle impingements during fracturing.

The rest of this paper is organized as follows. The numerical details are introduced in Section 2. Subsequently, results and discussions are presented in Section 3. Finally, main conclusions are briefly presented in Section 4.

2. Numerical details

2.1. Constitutive models

The strain of target material changes dramatically during the dynamic erosion process. Plastic strain and strain rate are important parameters that affect material behavior during particle collision. To study the dynamic erosion process, the plastic flow behavior of a target material was modeled using the Cowper–Symonds equation [27,28]. The Cowper–Symonds equation considers strain-hardening and strain-rate sensitivity. In the present study, the constitutive model is given as:

$$\sigma/\sigma_0 = 1 + \left(\dot{\varepsilon}/D_y\right)^{1/q} \quad (1)$$

where σ is the dynamic flow stresses, σ_0 is the static flow stresses, respectively, $\dot{\varepsilon}$ is the strain rate, D_y and q are constants of target material with values of 40 and 5, respectively. Under the multi-axial stress condition, σ and $\dot{\varepsilon}$ correspond to the equivalent dynamic flow stress and the associated equivalent strain rate, respectively.

To solve stress analysis, a modified CS model was developed for the uniaxial stress condition, which is described as:

$$\sigma = \sigma_0 \cdot \left[1 + \left\{\frac{\left(\varepsilon_u - \varepsilon_y\right)\dot{\varepsilon}}{\left(\varepsilon - \varepsilon_y\right)D_u + \left(\varepsilon_u - \varepsilon\right)D_y}\right\}^{1/q}\right] \quad (2)$$

where $\varepsilon_y \le \varepsilon \le \varepsilon_u$, ε_y is the yield strains, ε_u is the ultimate strains, D_y and D_u are the coefficients associated with ε_y and ε_u, respectively. D_u is a coefficient evaluated from the strain rate sensitivity properties at the ultimate tensile strength of a material. In the modified equation, the values of D_y, D_u, and q were 40, 6340, and 5, respectively. In Eq. (2), the strain hardening of the target material was not considered. Eq. (2) was modified by assuming the presence of linear strain hardening between yield strain ε_y and ultimate strain ε_u. To consider strain hardening, the strain hardening relationship between yield strain ε_y and ultimate strain ε_u was added in the equation and expressed as

$$\sigma = \sigma_0 \cdot (F + G\varepsilon) \cdot \left[1 + \left\{\frac{\left(\varepsilon_u - \varepsilon_y\right)\dot{\varepsilon}}{\left(\varepsilon - \varepsilon_y\right)D_u + \left(\varepsilon_u - \varepsilon\right)D_y}\right\}^{1/q}\right] \quad (3)$$

$$F = 1 - G\varepsilon_y \quad (4)$$

$$G = \left(\frac{\sigma}{\sigma_o}\right/ \quad (5)$$

where σ_0 and σ_u are the uniaxial static flow stresses at ε_y and ε_u, respectively.

2.2. Multiple particle impact

Material erosions that occur in most industrial applications are caused by continuous particle collision. During the fracturing process, proppants were carried in the fracturing fluid and injected through the pipeline under high pressure pump. The particles impacted the tool surface continuously and caused severe erosion wear. A multiple particle model was established to explore the dynamic process and mechanism. The continuous effect of an erodent can be considered in this model, which can reflect actual working conditions.

2.3. Material properties

Multiple particle erosion was simulated on the Q345 material. The mechanical properties of the target material, such as Poisson's ratio, yield strength, and Young's modulus at a temperature of 20 °C, are given in Table 1. The materials are assumed to be isotropic,