International Journal of Impact Engineering 75 (2015) 241–254

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Investigation on high-velocity impact of micron particles using material point method

Ping Liu [a], Yan Liu [a, b, *], Xiong Zhang [a], Yu Guan [c]

[a] School of Aerospace Engineering, Tsinghua University, Beijing 100084, China
[b] State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China
[c] Beijing Institute of Electronic System Engineering, Beijing 100854, China

ARTICLE INFO

Article history:
Received 4 October 2013
Received in revised form
24 June 2014
Accepted 3 September 2014
Available online 16 September 2014

Keywords:
High-velocity impact
Space debris
Material point method
Crater morphology mode

ABSTRACT

Continuous high-velocity impact of micro space debris and micro-meteroids may cause significant accumulative damages to spacecrafts. The process of high-velocity impact of micron aluminum particles on the aluminum target is investigated with the material point method (MPM). As a meshfree particle method, MPM is very suitable for solving high-velocity impact problems owing to its prominent advantages of dealing with fracture, fragmentation and moving material interface over the traditional mesh-based methods. The target plate is modeled as semi-infinite media since its thickness is much larger than the characteristic length of the projectile particles. The micron particles are projected to the target individually and in group with different angles and different velocities. The predicted impact responses and dimensions of the craters agree well with the experimental results and the empirical equations. The influences of the flux density, the projectile angle and the impact velocity are thoroughly investigated, and the morphology modes of the crater group are concluded. Finally, an empirical formula is proposed for the crater depth under impact of particle group.

1. Introduction

Natural meteoroids and man-made space debris particles are threatening the safety of near-earth orbiters. Every spacecraft in orbit is exposed to a certain flux of impacting particles, especially the millimeter-sized or micron particles. The impact risks need be assessed and shielding measures must be taken to avoid the failure or the decrease in performances of the space vehicles. Even after short exposure to the space environment, the surfaces will be covered with impacts from small-sized debris. The knowledge on impact from micron particles can be obtained through dedicated *in situ* experiments or through the analysis of the crafts returned from space, e.g. satellites or parts thereof [1,2]. Till now, the experiments of high-velocity impact need specially strict conditions and advanced equipments, which may cost a large amount of money and time. What's more, the situations in low earth orbit cannot be exactly reproduced or even the desired velocity conditions cannot be reached, not to mention that it is difficult to obtain and analyze the experimental data. Computational simulations are necessary ways to investigate the processes of high-velocity impact of materials.

In high-velocity impact, the magnitude of the stress wave is usually much larger than the strength of the projectile and the target, which makes extremely large local deformation and local failure of the material. This characteristic of high-velocity impact process brings many challeges to computational methods.

In the early stage of high-velocity impact research, Lagrangian or Eulerian mesh-based method were popular [3]. In Lagrangian mesh-based method, large deformation will lead to element distortion [4], which result in sharp decrease in time step size and the computation will abnormally terminate if the volume becomes very close to zero and even negative [5]. Eulerian mesh-based method, on the other hand, has the difficulty in tracking history variables and material interfaces [6]. Arbitrary Lagrangian–Eulerian method (ALE) combined the ideas from both the methods to overcome the above disadvantages [7], but the treatment of complex 3D problems is still under investigation. Since mid 1990s, meshfree particle methods (also called as meshless methods) have been paid much attention to and have shown successful applications in problems involving in large deformation. Typical meshfree particle methods include smoothed particle hydrodynamics (SPH)

* Corresponding author. School of Aerospace Engineering, Tsinghua University, Beijing 100084, China. Tel.: +86 10 62789122.
E-mail addresses: yan-liu@tsinghua.edu.cn (Y. Liu), xzhang@tsinghua.edu.cn (X. Zhang).

http://dx.doi.org/10.1016/j.ijimpeng.2014.09.001
0734-743X/

method [8], element free Galerkin method [9], reproducing kernel particle method [10], material point method (MPM) [11], radial basis function collocation method [12,13], meshless weighted least-square method [14], and general particle algorithm method [15].

MPM was proposed by Sulsky et al. [11] as an extension of particle-in-cell method to solid mechanics. One set of Lagrangian points and one Eulerian background grid are used for discretization in MPM, as shown in Fig. 1. Lagrangian points carry all the physical variables, such as the mass, the density, the velocity, the stress, the strain, which can describe the deformation and the boundary of the material. The usage of Lagrangian points avoids the difficulties in Eulerian method that the history variables are not easy to be traced and the problems caused by convection terms. Eulerian background grid is used to solve momentum equations and to calculate spatial derivatives, which overcomes the shortcomings in Lagrangian method that large deformation causes element distortion. As the result, MPM owns the advantages of both Lagrangian and Eulerian methods but overcomes their difficulties, and can solve problems involving in extremely large deformation. In each step, the traced variables of Lagrangian points are mapped onto the Eulerian grid nodes. Then the momentum equations are solved on grid nodes, and the particle variables are updated by mapping variable increments back onto the points. Finally the deformed grid is abandoned. Different with other meshfree particle methods, the critical time step size in MPM is controlled by the element size of the background grid instead of the characteristic length between points. So a time step size close to the initial time step size can be used throughout the simulation, even when very large deformation happens. What's more, no neighbor point search is needed in MPM. MPM ensures single-valued velocity field automatically even if no specific contact algorithm is adopted, and very efficient contact algorithm [16] based on the usage of the grid can also be adopted in MPM. Compared with the other meshfree methods, MPM is a very efficient and stable method for simulating high-velocity impact problems [17].

Owing to the above advantages, MPM has been developed fast and applied in many areas. MPM can effectively solve the problems of extremely large deformation and moving discontinuities, such as impact problems [18], granual flow [19], explosion [20], dynamic fracture [21,22], fluid-structure interaction [23], and multiscale analysis [24]. MPM was firstly applied in impact problems by analyzing Taylor bar problems [18,25]. Ma et al. [26] studied the penetration into thin and thick targets under hyper-velocity impact with MPM. Huang et al. [27] analyzed the influences of the grid size and the particle size on the results of the high-velocity impact simulation. They obtained the debris cloud morphologies in good agreement with the experimental results. Liu et al. [24] proposed a multiscale framework for high-velocity impact process, which combined molecular dynamics (MD) and MPM. MD was used to determine equation of state (EOS) parameters from micro level. The parameters are then transfered to MPM to simulate the high-velocity impact process. Hugoniot curves and debris cloud shapes

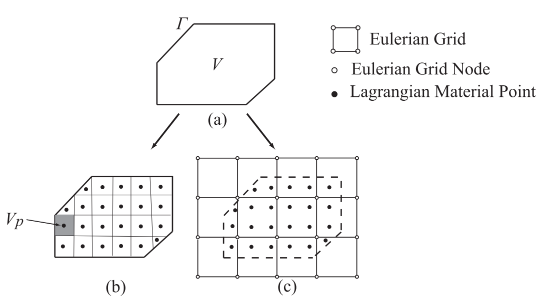

Fig. 1. Schematic diagram of discretization in MPM.

obtained with the multiscale framework agreed well with the experimental results. They proposed an empirical formula for the percentage of phase change material in high-velocity impact process based on a large number of simulations. Gong et al. [28] reproduced the micro-structure model of aluminium foam from CT images, and studied different Whipple shielding structures under high-velocity impact directly based on the MPM micro-structure model. Numerical results can predict well the damage and the holes on the shielding structure.

In this paper, the high-velocity impacts of micron particles are modeled and investigated with MPM. The main contribution of the paper is that the shape and the pattern of the craters caused by impact are thoroughly investigated and concluded, and the effects of the impact angle and the impact velocity are obtained. The result of particle group impact is firstly investigated with MPM, and an empirical equation is also proposed. The formulae of MPM are introduced in Section 2 focusing on the application in high-velocity impact process. The impact of single micron particle is simulated in Section 3, and the influences of different angles and velocities are studied. The impact of particle group is simulated in Section 4. The crater morphology is studied and categorized with different impact velocities and angles. The non-dimensional scaling analysis is carried out to derive the empirical formulae. The paper is concluded in Section 5.

2. Material point method and the material model

Discretized equations in MPM can be derived in updated Lagrangian formulation from the following governing equations on the current configuration.

$$\sigma_{ij,j} + \rho b_i = \rho \ddot{u}_i, \quad \text{in } \Omega \tag{1}$$

with the boundary conditions

$$u_i = \bar{u}_i, \quad \text{on } \Gamma_u \tag{2}$$

$$\sigma_{ij} n_j = \bar{t}_i, \quad \text{on } \Gamma_t \tag{3}$$

where $i,j = 1,2,3$ are spatial coordinate indices and Einstein summation convention is invoked. ρ and ρ_0 are the current and the initial material density, respectively. $\rho J = \rho_0$, where J is the determinant of the deformation gradient tensor $F_{ij} = \partial x_i / \partial X_j$. The superposed dot represents the derivative with respect to time, and "," is the spatial derivative. b_i is the body force per unit mass. $\bar{t}_i$ is the boundary surface traction. u_i is the displacement vector, and σ_{ij} is the Cauchy stress tensor. Γ_t and Γ_u represent the traction boundary and the displacement boundary, respectively. n_i is the unit outward normal vector of the boundary. The Cauchy stress can be decomposed as

$$\sigma_{ij} = -p\delta_{ij} + s_{ij} \tag{4}$$

where s_{ij} is the deviatoric stress component, $p = -\sigma_{ii}$ represents the pressure, and δ_{ij} is Kronecker delta symbol.

Inside each MPM step, the regular Eulerian background grid is binded to the Lagrangian points and deforms with the Lagrangian points in the same way. Any variables on the Lagrangian point can be interpolated from the grid.

$$f_p = f(\boldsymbol{x}_p, t) = \sum_{I=1}^{n_g} N_I(\boldsymbol{x}_p) f_I(t) = \sum_{I=1}^{n_g} N_{Ip} f_I \tag{5}$$

where the subscript I indicates the Eulerian grid node number, and the subscript p denotes the Lagrangian point number. $N_{Ip} = N_I(\boldsymbol{x}_p)$