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Numerical investigation of single and multi impacts of angular particles on ductile surfaces

Mehdi Azimian, Philipp Schmitt, Hans-Jörg Bart*

Chair of Separation Science and Technology, University of Kaiserslautern, 67663 Kaiserslautern, Germany

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ABSTRACT

Models of single and multi-particle impact(s) on metallic targets allow an understanding of fundamental erosion mechanisms. This work was focused on the creation of a three-dimensional finite element model of the single and multi-particle impacts on a ductile copper target using ANSYS Autodyn V. 14.57 tool. The finite element model was formulated in a Lagrange reference frame. Even at small initial impact velocities, the Lagrange formulation suffered from large material deformation and large element distortion. This resulted in an inefficient increase in simulation time. Therefore, element erosion approach was used to remove the highly distorted elements that were responsible for the time step problems. The copper plate was modeled with a shock equation of state in order to consider the shock propagation as realistic as possible. The Johnson–Cook strength model was used in combination with the Johnson–Cook failure model. Good agreement between simulation results and experimental data was obtained. Moreover, a parameter analysis was carried out by varying the initial input conditions. Erosion mechanisms, such as cratering by material pile-up and chip formation were observed. It was found that mainly the initial orientation angle of the particle θ_i, and the impact angle α_i, determine the erosion mechanism. For a given constant impact angle α_i, there is a specific initial orientation angle θ_s, in which the transition from kinetic energy into internal energy is maximized. For values of $\theta_i < \theta_s$, the particle rotated forwards after the impact with the copper plate. For initial orientation angles $\theta_i > \theta_s$, the particle rotated backwards after the impact. The modeling was performed with multi-particle impacts as well. It was found that the rising rate of penetration depth decreases gradually when the number of non-overlapping particle impacts has increased.

1. Introduction

Impact of particles causing material removal is an important phenomenon present in many industrial applications including blast cleaning, paint blast stripping from automobiles, erosion of pipelines and turbo-machineries, erosive drilling of hard materials, abrasive micromachining of components for applications such as micro-electro mechanical systems (MEMS), opto-electronic and micro-fluidic. In all of these cases, which can be constructive or destructive, material removal occurs due to presence of a large number of spherical or irregular angular particles carried usually in fluid streams [1]. Azimian and Bart [2–5] have investigated the erosion due to the two-phase liquid–solid flows in some various cases experimentally and numerically in detail. However, in fundamental research, it is worth to investigate the single particle impacts and the controlled multi-particle impacts for investigation of erosion mechanisms. In this way, Hutchings [6,7] presented that the crater volume, shape and rebound parameters can be successfully predicted for collisions between both spherical and non-spherical (square) particles and various target materials. This was done by assuming the particle as rigid and the target with a fully plastic behavior. Papini and Spelt [8] analyzed the erosion of substrates of arbitrary dynamic hardness and friction coefficient due to the impact of individual angular particles. They have developed a rigid-plastic theory due to Hutchings [6] for square plates impacting frictionless surfaces, for arbitrarily shaped particles impacting ductile surfaces.

For experimental investigations, Hutchings and Winter [9] in 1974, applied a relatively simple and inexpensive small bore gas gun using moderate gas pressures to study the impact of small solid particles at velocities up to 600 m/s. Hutchings et al. [10] in 1977, designed a rectangular bore gas gun to avoid the axial rotation of the projectile, which may occur in a cylindrical bore gun. The gas guns with cylindrical bores allow the projectile to

* Corresponding author. Tel.: +49 631 2052414.
E-mail address: bart@mv.uni-kl.de (H.-J. Bart).
URL: http://www.mv.uni-kl.de/tvt (H.-J. Bart).

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rotate axially during its way down the barrel. Although such rotation is usually small, it is not reproducible for impact experiments in which precise projectile orientation at the impact point is desired. This degree of freedom may be a serious drawback. Therefore, a barrel of rectangular cross section was used to overcome the problem. Hutchings et al. [10] used projectiles of 0.5 g weight and accelerated them to the velocities up to about 300 m/s. It was also approved that helium must be used instead of nitrogen as the propellant gas for operations at higher velocities. A laboratory scale gas gun and associated tools have been designed by Brown et al. [11] in 1989 as a tool for transverse impact experiments on composite materials at velocities in the range of 200–750 m/s, using projectiles of 5.59 and 7.62 mm diameter. A good agreement was achieved between the measured projectile velocities and those calculated from an approximate theoretical dynamic gas model. This model considered the propagation of rarefaction waves in the gas reservoir and the air pressure build-up in the barrel in front of the projectile. A novel experimental tester as a catapult apparatus was designed and constructed by Dhar et al. [1] in 2005 to launch the particles. The catapult was loaded manually by pushing down the launching end of the arm until it was locked into the release mechanism. The particle was held by a holder in place, which is attached to a lever arm. A high-speed digital camera was used to measure impact and rebound parameters. Their experimental results [1] were compared to the predictions of a rigid-plastic model and very good agreement was found with respect to the energy losses. Papini and Dhar [12] have experimentally verified a previously described rigid-plastic model of the erosion of ductile targets by the impact of single angular particles [8,13] over a wide range of particle angularities, initial impact angles and initial orientation angles. Similar to the experimental tester of Hutchings et al. [10], Takaffoli and Papini [14] applied a compressed nitrogen gas gun with a rectangular cross-section barrel. During acceleration within the barrel, the particle was held in a Lexan sabot, which had a sliding fit in the gun barrel. Their gas gun design was in a way so that the impact could be considered as two-dimensional and by setting the nitrogen pressure, various impact velocities could be achieved. Impact and rebound parameters were measured with the help of a high-speed camera here as well. Moreover, a non-contact optical profilometer was used to measure the 3D profile of the craters and its volume together with the maximum depth of crater and the height of material pile-up. Regarding the modeling studies in this field, the finite element method (FEM) has been recently applied comprehensively in the modeling of single particle impacts to study residual stress states resulting from hard-body impact [15], to estimate the crater's depth developed in the target material by abrasive water jet machining [16] and to predict the erosion rate for mild steel, cast iron and Ti–6Al–4V alloy [17,18]. Takaffoli and Papini [14] used a 2-D FEM model of particle and target to predict the single impacts of angular particles on ductile surfaces with oblique impact angles and high impact velocities. They could show that the chip formation and the material pile-up, two phenomena that cannot be simulated using a rigid-plastic model, could be simulated by the FE models, achieving results in quite good agreement with experimental data. Wang and Yang [19] carried out a coupled finite element and mesh-free analysis of erosive wear for multiple non-overlapping spherical particles impacting a ductile target. Liu et al. [20] have recently applied FEM to study the effect of various particle shapes on the erosion of ductile materials.

In present paper, the specific case of angular particles which are symmetrical, but of arbitrary angularity is discussed in detail. The present model also considers the effects of friction and is used to predict the crater volume and rebound parameters (such as angle, velocity and angular velocity) for symmetrical, rigid and angular particles of specific size, initial orientation and angularity. In this way, the same particle and target materials as presented also by Takaffoli and Papini [14] were modeled under the identical input/boundary conditions in the experimental tests (Table 3) carried out by Takaffoli and Papini [14]. However, a 3D FEM model was generated here and was modeled by applying some modifications. Moreover, the multi non-overlapping particle impacts were simulated under identical boundary conditions as by single impacts. In this way, it is possible to observe the effects of multiple impacts on the variation rate of penetration depth. Numerical simulation modeling is presented here and is validated by comparison with the experimental data [14].

2. Modeling

A definition of the characteristic particle parameters impacting a target surface is presented in Fig. 1. v_i is the initial impact velocity of particle on to the target surface, α_i is the impact angle, which is the angle between the velocity vector and the surface horizontal axis, θ_i is the initial orientation angle, which is the angle between the vertical axis of target surface passing from the center point of the particle and the diagonal of the particle shown in Fig. 1. Angularity of the particle is represented with A and is defined in Fig. 1 as well. The initial rotation $\dot{\theta}_i$ was 0 rad/s for all the experiments. To find out the erosion behavior and trend, initial velocity v_i, impact angle α_i and initial orientation angle θ_i were varied. Experimentally, this was achieved by pressure variation, adjusting the inclination of the target plate and the use of different holding devices for the particles. The variation of these parameters can have a decisive influence on whether the particle would rotate backwards or forwards during the rebound after the impact with the surface. In experimental work [14], the target material was fixed on the ground and on the outer sides, thus only permitted deformations on the target surface and inside the body where the impact of the particle was to be expected. The particle had a definite 3D rhomboid geometry (see Fig. 2), material properties and initial impact conditions. Particle and target had from the beginning of the simulation a line contact to save unnecessary computational time. Another strategy to reduce the simulation time, was the symmetrical assumption of the angular particle. The contact between the particle and the target surface was modeled by the penalty method. By sliding, a constant dynamic coefficient of friction was assumed as 0.1. To model the experiments described above, the ANSYS Autodyn x64 V. 14.57 tool was used. The geometry was modeled three-dimensionally in original size and was discretized by hexahedral elements. Fig. 2 shows the finite element model of the particle and target for the experiment case 2 as an example. The penetration of a particle into the target material results in a change of the originally flat surface. Fig. 3 presents how the penetration depth (d_{max}) and the lip height (h_{lip}) are defined for each crater due to the particle impact. Arising small time steps in explicit dynamics required an extremely long simulation time. Therefore, a numerical integration was used, which saved the computational time and resulted in better capturing of the structural behavior. As the numerical integration, the Gauss method was applied here. However, a lower integration leads to the problem of numerical hour-glassing. This must be properly controlled to achieve accurate results. Therefore, an hourglass damper was used during the integration to minimize this problem.

In order to achieve the best results close to reality, it is important to run the simulations as mesh independent. This means that the simulation results would not further vary sensibly by further refinement of the geometry's mesh. However, in many cases, specially for complex geometries or complex simulations,