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Simulation of natural fragmentation of rings cut from warheads

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Abstract

Natural fragmentation of warheads that detonates causes the casing of the warhead to split into various sized fragments through shear or radial fractures depending on the toughness, density, and grain size of the material. The best known formula for the prediction of the size distribution is the Mott formulae, which is further examined by Grady and Kipp by investigating more carefully the statistical most random way of portioning a given area into a number of entities. We examine the fragmentation behavior of radially expanding steel rings cut from a 25 mm warhead by using an in house smooth particle hydrodynamic (SPH) simulation code called REGULUS. Experimental results were compared with numerical results applying varying particle size and stochastic fracture strain. The numerically obtained number of fragments was consistent with experimental results. Increasing expansion velocity of the rings increases the number of fragments. Statistical variation of the material parameters influences the fragment characteristics, especially for low expansion velocities. A least square regression fit to the cumulative number of fragments by applying a generalized Mott distribution shows that the shape parameter is around 4 for the rings, which is in contrast to the Mott distribution with a shape parameter of ½. For initially polar distributed particles, we see signs of a bimodal cumulative fragment distribution. Adding statistical variation in material parameters of the fracture model causes the velocity numerical solutions to become less sensitive to changes in resolution for Cartesian distributed particles.

Keywords: Warhead; Fragmentation; Simulation; Fracture models; Expanding ring; Smooth particle

1. Introduction

Most conventional weapons contain some type of explosive charge encased in a steel metallic container. When the explosive filling of a shell or a bomb detonates, the casing is subjected to an extreme high pressure from the gaseous products of the detonation. The casing ruptures and a number of fragments that vary greatly in size are produced. During natural fragmentation the spatial shape and velocity distributions are probabilistic because of the strength of the casing and the nature of the shock wave that gives the detonation. Rigorous hydrocode calculations can offer insight into the physics of fragmentation. However, no first principle calculations can currently be used for calculating the correct fragment size distribution. This deficiency may be due to the lack of viable fracture models during high rates of strain or microstructure variations that are not accounted for. However, hydrocode accuracy may also play a role due to the stochastic or chaotic nature of the fragmentation process.

The fracture behavior of steel rings, taken from a 25 mm steel warhead is studied. To reach high strain rates around 10^4/s, an expanding ring test was performed. A streak camera was used to examine the radial ring velocity, and a water tank was used to collect the fragments (Moxnes et al., 2014 [31], Moxnes et al., 2015 [32]). The fracture strain in the standard Johnson–Cook (hereafter abbreviated J-C) fracture model (1985) [25] is deterministic. Current research in the literature on fracture/failure models focus on the dependency of fracture/failure strain on triaxiality (the ratio of the invariant I_1 to J_2) or even the third invariant, strain rate influence on ductility,

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element size and the connection to adiabatic shear bands during high rates of strain. Goto et al. (2008) [17] and Grady and Hightower (1990) [13] investigated the fragmentation size of explosively driven rings and cylinders. The data were used to determine relevant coefficients for the J-C fracture model. A quasi-static strength model of the steel was established by using a smooth uniaxial tensile test to find the von Mises flow plastic function in a J-C (1983 [24], 1985 [25]) strength model. The parameters of the J-C fracture model were found using the results from quasi-static tensile tests on three different sample geometries (Moxnes et al., 2014 [31]). However, variations in the micromorphology of the material may lead to variations in fracture strain that may be important in fragmentation studies.

The first intriguing stochastic approach to the fragmentation problem was to investigate the statistical most random way of portioning a given topology into a number of discrete entities. Mott and Linfoot (1943) [34] referred to an earlier work of Lineau (1936) [29] for the description of fragmentation of ammunition based on this purely stochastic principle. The best known formula for the prediction of the size distribution is the Mott cumulative fragment mass formulae (Mott and Linfoot 1943 [34]; see Appendix A for details), which is further developed by Grady and Kipp (1985) [15] by investigating more carefully the statistically most random way of portioning a given area into a number of discrete entities. The derivative of the Mott formulae is a two-parameter Weibull distribution which is infinite at zero mass. The literature gives possible modifications to account for maximum and minimum fragment size. See Cohen (1980) [5], Grady and Kipp (1985) [15], Strømsøe et al. (1987) [39], Grady (1990) [14] and Baker et al. (1992) [1] for further studies in geometric fragmentation statistics. Grady (1990) [14] developed a theory for the statistical fragmentation based on the Poisson process for masses or for areas. The Weibull distribution has been used for fracture statistics for brittle materials (Lu et al., 2002) [27]. A method for analyzing the mass distribution was developed where the cumulative fragment mass is plotted as a function of cumulative fragment number, i.e. beginning with the heaviest fragment (Held and Kühl 1976 [20], Held 1990 [21], Held 1991 [22]).

Metals have a microstructure whose details may create variations in material strength and strain to fracture. Rather than explicitely model the microstructure one attempts to calculate some effects of material inhomogeneity by a physical based statistical description. In a later work, Mott (1947) [33] assumed that fractures occurred at random around the circumference of the ring of a casing at a frequency governed by a strain dependent hazard function. Mott used tensile test data on steels to investigate parameters of the hazard function and provided some analytical solutions. It should be emphasized that this second model by Mott bears no relationship to the earlier Mott distribution derived by Mott and Linfoot (1943) [34]. Moreover, computer codes can provide details on fragmentation behavior, and more easily use the stochastic fracture approach as developed by Mott (1947) [33]. However, the spatial scale of the microstructure is typically of the order of micrometers and is currently not readily accessible to computational tools and resources for system level calculations. To account for microstructure physics or even adiabatic shear banding at the sub-grid level, a statistical approach may indeed be useful. A current research area is whether statistical fracture in constitutive models predicts the size distribution of fragments better than a homogeneous fracture model (Haldorsen and Moxnes 1998a [18] and 1998b [19], Glansville et al., 2010 [11], Hopson et al., 2011 [23], Meyer and Brannon 2012 [30], Rakvåg et al., 2014 [38], Moxnes et al., 2015 [32]). Hopson et al. (2011) [23] concluded by using a Eulerian code that a statistically compensated J-C fracture model substantially improved the fragmentation mass distribution for an explosive loaded cylinder. The homogeneous solution produced larger fragments in comparison to the Weibull solutions and the test data. Meyer and Brannon (2012) [30] concluded that using a Eulerian code with inherent variability in the continuum mechanics simulations lead to more realistic predictions. The statistical J-C fracture model achieved better predictions of the intermediate-sized fragments. It was concluded that proper ways to incorporate sub scale physical effects in strength and fracture models remains a subject of research. Moxnes et al. (2014) [32] show by using smoothed particle hydrodynamics (SPH) that randomness increased the number of fragments.

Another research issue is whether numerical noise is useful without any stochastic fracture model (Diep et al., 2000 [7], Diep et al., 2004 [8], Prytz and Ødegårdstuen 2011 [36], Cullis et al., 2014 [6], Moxnes et al., 2014 [31], 2015 [32]). The interesting aspect of numerical noise is that it does not require any artificial seeding of fracture sites within the material as a part of the initial conditions of the problem. However, mesh sensitivity makes results of fracture models difficult to validate (Brannon et al., 2007 [3]). Glansville et al. (2010) [11] found that mesh sensitivity was significantly reduced in the explicit Autodyn Lagrangian code when applying volume scaling in a Weibull distribution. Meyer and Brannon (2012) [30] concluded that further studies were warranted to ensure mesh independence of the predictions and accuracy in a variety of applications. Moxnes et al. (2014) [31] show by using SPH that increasing the resolution (i.e. reducing the particle size) increased the number of fragments.

Particle methods such as smoothed particle hydrodynamics (SPH) show tremendous potential for fragmentation simulations since they support both arbitrary large deformations and Lagrangian state variable tracking that avoids corruption by advection errors. SPH is a Lagrangian technique (Gingold and Monaghan 1977 [10], Lucy 1977 [28], Benz 1990 [2]) based on two main assumptions: First, an arbitrary scalar field variable can be estimated at any point in space by multiplying the variable by a suitable weight kernel and integrating over the entire simulation domain. The scale length of the weight kernel is referred to as the smoothing length, and in practice, the kernel has compact support so that the integral can be restricted to a relatively small volume. Secondly, the continuous integral is replaced by a discrete sum over a finite set of interpolation points (the particles). The gradient of the variable