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Experimental and numerical study of the fragmentation of expanding warhead casings by using different numerical codes and solution techniques

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Abstract

There has been increasing interest in numerical simulations of fragmentation of expanding warheads in 3D. Accordingly there is a pressure on developers of leading commercial codes, such as LS-DYNA, AUTODYN and IMPETUS Afea, to implement the reliable fracture models and the efficient solution techniques. The applicability of the Johnson–Cook strength and fracture model is evaluated by comparing the fracture behaviour of an expanding steel casing of a warhead with experiments. The numerical codes and different numerical solution techniques, such as Eulerian, Lagrangian, Smooth particle hydrodynamics (SPH), and the corpuscular models recently implemented in IMPETUS Afea are compared. For the same solution techniques and material models we find that the codes give similar results. The SPH technique and the corpuscular technique are superior to the Eulerian technique and the Lagrangian technique (with erosion) when it is applied to materials that have fluid like behaviour such as the explosive and the tracer. The Eulerian technique gives much larger calculation time and both the Lagrangian and Eulerian techniques seem to give less agreement with our measurements. To more correctly simulate the fracture behaviours of the expanding steel casing, we applied that ductility decreases with strain rate. The phenomena may be explained by the realization of adiabatic shear bands. An implemented node splitting algorithm in IMPETUS Afea seems very promising.

Keywords: Warhead; Fragmentation; Simulation; Fracture model

1. Introduction

When a warhead detonates, the resulting terminal effects in the target are dependent on the velocity and physical characteristics of the fragments. However, it is notable that, for blast-frag warheads, the total damage to the target is the results of blast and fragments acting together in a synergistic manner.

The initial fragment velocity is not very dependent of material properties, such as hardness, strength and ductility. It is well known that the same is true for changes in the geometrical aspects of casing design, such as 1) the use of shear-control grids on either the inner or outer surface of the casing; 2) different control sizes in the dimensions of the diamond pattern grids; and 3) variations in the cross sectional profiles of the grid elements.

The main controlling parameter for initial fragment velocity from expanding warhead is the charge over mass

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relation of the warhead, as described by Gurney, based on the energy balance approach [1]. For expanding thin walled casing, the strain rate is typically in the range of 10^4–10^5/s. The natural fragmentation process for a steel casing may start with the initiation of shear fracture at the outer or inner surface of the casing. The fracture then proceeds through the wall of the casing following the trajectories of maximum shear. However, the radial fractures could be initiated and dominate in the outer tensile region.

An elasto-plastic body that is homogeneously deformed will ultimately fail at a single random located imperfection. After failure is initiated, the static loads decrease so that the quasi-static stresses are no longer sufficient to trigger multiple fracture surfaces. However, when the same body is homogeneously deformed at high strain rates fragmentation can occur since initiation sites are isolated by wave propagation effects. A fracture that develops at one location can only influence the stress or strain at a neighbouring location after a finite delay time. This delayed interaction between initiation sites provides time for crack growth at neighbouring sites. Although the fractures resulting in fragmentation are randomly located, the fragmentation size distribution depends on the deformation, the fracture characteristics of the material and the interactions with neighbouring fractures.

In metals, the nucleation of micro voids and/or micro cracks can grow under tension. The fracture process in metals is now known to be caused by nucleation of micro voids or micro cracks, micro void and micro crack growth, and finally coalescence of voids or cracks to form macro cracks. Brittle materials form planar, circular micro cracks. Ductile metals show spherical micro voids [2–5]. Under compression, micro shear bands can nucleate and grow into shear bands.

Changes through wide ranges of such properties of steel casing, such as hardness, strength and ductility, can produce the marked changes in the geometrical configuration of the fragments produced. To simulate fragmentation of, for instance, an expanding warhead, the accurate material strength and fracture models are necessary. Recent experiments on metals have shown that both pressure and the Lode [6] variable may be included in the flow curve for some materials. Bai and Wierzbicki [7] developed a model for metal plasticity and fracture with pressure and Lode dependency. The nucleation and fracture coalescence depends on pressure or triaxiality, that means on the proportion of the invariant I_1 to J_2 [8,9]. It has been questioned whether triaxiality fully can describe isotropic ductility. It has been shown that the internal necking of ligament between voids that have grown significantly dominates at high triaxiality, while the internal shear localization of plastic strain ligament between voids that have experienced limited growth dominates at low stress triaxiality [10].

To quantify the influence of stress triaxiality on ductility, the different experiments on smoothed and notched bars are traditionally utilized [11]. In general, the larger the triaxiality is, the smaller the strains are at fracture. This is in agreement with theoretical models for void growth [12,13]. However, McClintock [12] and Johnson and Cook [14] found that the plastic strain to fracture was smaller in torsion (no triaxiality) compared to tension (larger triaxiality) for many materials. Recently, Bao and Wierzbicki [15] and Bao and Wierzbicki [16] compared the different models to cover the influence of triaxiality. They concluded that none of the models were able to capture the behaviour in the entire triaxiality range. For large triaxialities (above 0.4), void growth was the dominating fracture mode, while at low triaxialities the shear of voids dominated. The main conclusion was that there is a possible slope discontinuity in the fracture locus corresponding to the point of fracture transition [16]. Bao and Wierzbicki [38] found a cut-off value of the stress triaxiality to $-1/3$ below which fracture never occurs. Teng and Wierzbicki [39] evaluated six fracture models in high velocity perforation.

A Lode parameter dependency has therefore been proposed. Wilkins et al. [17] noticed that the combination of hydrostatic tension and shear is related to the mechanism of ductile fracture. They concluded that the order of the applied loads, i.e., hydrostatic load followed by shear load or vice versa, should be important in fracture modelling.

Phenomenological continuum damage models have been developed to account for failure and fracture. To account for the order of the applied loads, the cumulative damage criterion has been applied [17]. It is assumed that the failure occurs at a point of the material where a weighted measure of the accumulated plastic strain reaches a critical value. The weighing function depends on the triaxiality. An appropriate weighting function is still an active field of research [7,18]. In the Johnson–Cook (J–C) model used herein, an uncoupled (passive) damage evolution formulation with no Lode dependency is adopted, which entails that there is no coupling between the stress–strain behaviour and the damage evolution until a failure occurs at the critical damage.

Shear localization due to adiabatic shear band that is much smaller than the element size can soften the material. The greater the shear strain rate is, the larger is a number of these shears bands generated, and hence there is a lower stress for a given strain. This unstable thermoplastic shear occurs locally in the shear bands when the local flow stress decreases with the increase in strain. This happens when the rate of thermal softening due to the internally generated heat exceeds the rate of isothermal work hardening. The shearing deformation could even be so intense as to cause melting of the material in the bands. The temperature rise in the adiabatic shear bands should not be confused with the bulk temperature rise of the metal on the element size undergoing deformation under adiabatic conditions [19].

The Lagrangian processor, in which the numerical grid distorts with the material, is computationally fast and gives good definition of material interfaces. However, the ability of the Lagrangian processors to simulate the explosive events can usually only be enhanced by use of an erosion algorithm. The erosion algorithm works by removing Lagrangian zones which have reached a user-specific strain, typically in the order of 100–150%. The Eulerian processor, which uses a fixed grid through which material flows, is computationally much more expensive then the Lagrangian process, but is often better