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Strain rate dependency and fragmentation pattern of expanding warheads

John F. MOXNES [a,*], Anne K. PRYTZ [b,2], Øyvind FRØYLAND [a,1], Stian SKRIUDALEN [a,1], Steinar BØRVE [a,1], Gard ØDEGÅRDSTUEN [b,2]

[a] *Land Systems Division, Norwegian Defence Research Establishment (FFI), P.O. Box 25, NO-2027 Kjeller, Norway*

[b] *Nammo Raufoss AS, P.O. Box 162, NO-2831 Raufoss, Norway*

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Abstract

For the characterization of the behaviors of a metal material in events like expanding warheads, it is necessary to know its strength and ductility at high strain rates, around 10^4-10^5/s. The flyer plate impact testing produces the uniform stress and strain rates but the testing is expensive. The Taylor test is relatively inexpensive but produces non-uniform stress and strain fields, and the results are not so easily inferred for material modeling. In the split-Hopkinson bar (SHB), which may be used in compression, tension and torsion testing, the strain rates never exceeds 10^3/s. In the present work, we use the expanding ring test where the strain rate is 10^4-10^5/s. A streak camera is used to examine the expanding ring velocity, and a water tank is used to collect the fragments. The experimental results are compared with the numerical simulations using the hydrocodes AUTODYN, IMPETUS Afea and a regularized smooth particle (RSPH) software. The number of fragments increases with the increase in the expansion velocity of the rings. The number of fragments is similar to the experimental results. The RSPH software shows much the same results as the AUTODYN where the Lagrangian solver is used for the ring. The IMPETUS Afea solver shows a somewhat different fragmentation characteristic due to the node splitting algorithm that induces pronounced tensile splitting.

Keywords: Warhead; Fragmentation; Simulation; Fracture model; Expanding ring

1. Introduction

Plasticity-based analytical modeling and finite element methods (FEM) may be used to predict the fragmentation pattern of warheads. However, the viability of the predictions relies on the material constitutive models describing the plastic flow stress and fracture. For an expanding thin wall casing, the tangential strain rates are typically in the range of 10^4-10^5/s and the quasi static established material model may not be viable. Main research issues are the dependency of fracture strain on triaxiality (that means on the proportion of invariant I_1 to J_2), the influence of the third invariant, i.e., strain rate, on ductility, element size and the connection to adiabatic shear bands at high strain rate, and whether statistical failure predicts the size distribution of fragments better than a homogeneous failure model [1−6].

Failure process of ductile materials is caused by the nucleation, growth and coalescence of voids to fracture. The fracture coalescence depends on pressure or triaxiality (that means on the proportion of invariant I_1 to J_2) [7]. In general, the larger the triaxiality is, the smaller the fracture strain at failure becomes. This is in agreement with theoretical models for void growth [8,9]. Recently, Bao and Wierzbicki [10,11] compared the different models to cover the influence of triaxiality. They concluded that none of the models were able to capture the fracture behavior in the entire range of triaxiality. The void growth was the dominated ductile failure mode

* Corresponding author. Tel.: +47 63 807514, +47 63 807000; fax: +47 63 807509.

E-mail address: john-f.moxnes@ffi.no (J.F. MOXNES).

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[1] Tel.: +47 63 807000.

[2] Tel.:+47 61 153609.

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at large triaxialities (say above 0.4), while the shear of voids dominates at low triaxialities. The main conclusion was that there was indeed a possible slope discontinuity in the fracture locus corresponding to the point of fracture transition [11]. A dependency of the third invariant has been forecasted.

Both yield strength and ultimate tensile strength usually increase with strain rate for steel materials. The ductility of quenched and tempered steel may increase with strain rate, while the ductility of the material which high strength is achieved by precipitation hardening process may decrease with strain rate. Body-centered cubic (bcc) materials can also behave different from face-centered cubic (fcc) materials. Thermal softening decreases strength and increases ductility. Thus the ductility of materials could increase with small strain rates but could decrease with higher strain rates due to thermal softening. Decreased ductility at higher strain rates may be explained by shear localization due to adiabatic heating [12]. Unstable adiabatic shear transfers the entire burden of strain to a finite number of these shear planes (adiabatic shear bands). Due to restriction on computational time, the element sizes are traditionally too coarse to resolve the shear bands by direct simulation.

Wilkins et al. [13] concluded many years ago that the order of the applied loads, i.e. hydrostatic pressure followed by shear or vice versa, should be important in failure modeling. To account for the order of the applied loads, the cumulative damage criterion has been applied [13]. Fracture 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 and/or the third invariant I_3. Finding an appropriate weighting function is still an active field of research [14,15]. In the Johnson−Cook (J−C) model [16], an uncoupled (passive) damage evolution formulation with no third invariant dependency is adopted, which entails that there is no coupling between the stress-strain behavior and the damage evolution until fracture occurs at the critical damage.

The split-Hopkinson bar (SHB), which may be used in compression, tension and torsion testing, is the most widespread method for material high strain rate characterization. However the strain rate never exceeds 10^3/s and is thus much lower than that achieved under explosive loadings. Many ductile materials display an increase in yield stress for strain rates above 10^3/s [17,18]. It is challenging to conduct material tests at the strain rates of larger than 10^3/s. The flyer plate impact testing produce uniform stress and strain rates but the testing is expensive. The Taylor testing is relatively inexpensive and data could be obtained from simple post-test measurements. However, the Taylor test produces non-uniform stress and strain fields and the results are not so easily interpreted for material modeling.

In this article, the fracture behavior of steel rings, taken from a 25 mm warhead, is studied. To reach the strain rates of more than 10^3/s, an expanding ring test is performed. A streak camera was used to examine the ring velocity, and a water tank was used to collect the fragments [19].

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 strength model. The parameters of a J−C damage development model are found using the results from quasi static tensile tests in which three different sample geometries are used [20].

The Lagrangian processor is computationally fast and gives good definition of material interfaces. However, the ability of the Lagrangian processor to simulate explosive events can only be enhanced by use of an erosion algorithm which removes the zones that have reached a user-specific strain, typically in the order of 75%−150%. The Eulerian processor, which uses a fixed grid through which material flows, is much more expensive in calculation than the Lagrangian processor, but is well suited for modeling larger deformations and fluid flow. See Refs. [21,22] for use of Eulerian CTH code. See Refs. [23,24] for use of the Arbitrary-Lagrangian-Eulerian ALE3D/CALE codes and Ref. [25] for semi-empirical-numerical methods.

The smooth particle hydrodynamics (SPH) method is a Lagrangian technique [26]. This grid-less technique does not suffer from the problem associated with the Lagrangian technique of grid tangling in large deformation problems. SPH is based on two main approximations of the continuum equations. First, an arbitrary scalar field variable is described by an integral over the space that is only approximate since a smoothed kernel is used in the integral instead of the exact Dirac delta function. Second, this integral is approximated by a discrete sum of a finite set of interpolation points (the particles). In AUTODYN and LS-DYNA, SPH nodes interact with Lagrangian surfaces. This allows to model the regions which undergo small deformations using the Lagrangian processor, while those regions experiencing large deformations (i.e. the explosive) can be modeled using SPH. The most well-known problem with SPH is loss of stability due to tensile instability and artificial fragmentation due to large particle spacing relative to the smoothing length. Regularized smooth particle hydrodynamics (RSPH) was developed to increase accuracy in shock wave modeling [27]. In the current work, the original RSPH code has been extended to study the fragmentation of solids with a state of the art handling of tensile instability [28] and a sufficiently small ratio between the original particle spacing and the smoothing length.

We also apply the IMPETUS Afea node splitting algorithm and the corpuscular model. The corpuscular method does not start from the continuum equations, but postulate a number of particles that interact by collisions [29,30]. In the Lagrangian solver, instead of eroding cells that fails, the nodes can split, resulting in a sort of crack propagation. These cracks are constrained by the mesh, or cell size.

2. Experimental setup and geometrical data

Figs. 1 and 2 show the setup. The brass tubes with constant outside diameter and variable inside diameter were loaded with the explosive, which is modeled as composition LX10. Steel rings were manufactured from projectile bodies of the in-service round. To find the velocity of the rings, the test item is placed such that the expansion of the ring is perpendicular to