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Ballistic resistance of high hardness armor steels against 7.62 mm armor piercing ammunition

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ABSTRACT

Although advanced lightweight composite based armors are available, high hardness steels in military vehicles are often used to provide ballistic protection at a relatively low cost and is an interesting material due to its widespread usage in vehicle structure. In this study, ballistic limit of 500 HB armor steel was determined against 7.62 mm 54R B32 API hardened steel core ammunition. Lagrange and smoothed particle hydrodynamics (SPH) simulations were carried out using 3D model of bullet and high hardness armor target. Perforation tests on 9 and 20 mm thickness armor were performed to validate simulation methodology. Also material tests were performed for armor steel and ammunition hardened steel core to develop Johnson–Cook constitutive relations for both strength and failure models. Finally, results from 3D numerical simulations with detailed models of bullet and target were compared with experiments. The study indicates that the ballistic limit can be quantitatively well predicted independent of chosen simulation methodology, but qualitatively some differences are seen during perforation and fragmentation. As shown in results, good agreement between Ls-Dyna simulations and experimental data was achieved by Lagrange formulation with the full bullet model.

1. Introduction

High velocity impact and penetration problems include large deformation, erosion, high strain rate dependent nonlinear material behavior and fragmentation. Therefore, it is important to model mechanical behavior of the penetration where above affects are taken into account. In reality since empirical and analytic approaches cannot capture all of multiple physical phenomena including fracture, failure, residual stresses and friction heating [1,2], numerical simulation has become a necessary tool for the ballistic penetration study. Numerical methods and corresponding computing technologies have been evolved to the level where mentioned complex deformation and penetration pattern during ballistic impact can be accurately predicted. The usage of numerical methods in the development of design alternatives will not only introduce shorter armor development time, but also will reduce the number of prototypes to minimize the number of the real scaled field tests required, and also help us to visualize the impact behavior.

A review of the literature on impact simulations show that the most research in this field have been focused on the development and application of continuum hydro-codes using either mesh based Lagrangian or mesh free formulations [3–6]. Lagrange formulation is widely used because of its advantages, such as low level of computational cost, being able to track accurately and efficiently material interfaces and incorporate complex material models [7]. Accurate and realistic simulation of ballistic penetration with Lagrange formulation requires complicated contact and erosion algorithms. However, it is very sensitive to distortions resulting small time steps and possible loss of accuracy. The well known negative volume errors occur as a result of such mesh tangling issues. Numerical codes can handle these problems with adaptive re-meshing algorithms or by eroding the highly distorted elements with artificial manipulation which can cause loss of accuracy. On the other hand, high computational cost of adaptive re-meshing algorithms and its limited applicability on three dimensional problems decrease the attractiveness. As an alternative to mesh based Lagrangian formulation, smoothed particle hydrodynamics is a meshless computational technique, which has some special advantages over the traditional mesh-based numerical methods. Because of the adaptive nature of the SPH approximation, it can handle problems with extremely large deformations very well [8]. The SPH particles also carry material properties, functioning as both approximation points and material components. These particles are capable of moving in space, carry all computed information, and thus form the computational frame for solving the partial differential equations describing the conservation laws. In

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application, the principal potential advantage of the SPH method is that there is no need for connectivity between particles with a conventional mesh, hence avoiding element distortion problems at large deformations [9].

A popular explicit code, Ls-Dyna was successfully used to simulate several types of armors subjected to impact ammunition for various threat levels and capable of applying both Lagrange and SPH methods. Earlier studies on steel plates impacted by various projectiles [10–17] show that, ballistic penetration behavior can be simulated using either Lagrange or SPH. Borvik et al. [12] considered ballistic penetration performance of five different steel alloys, yield strengths ranging from 600 to 1700 MPa with Lagrange discretization. They demonstrated that, compared experimental and numerical studies show reasonable agreement in determination of ballistic limit velocity. There is almost a linear correlation between ballistic limit velocity and yield strength and for BR7 level armor piercing ammunition yield strength shall be around 1500 MPa for 12 mm target. Dey et al. have been studied ballistic perforation resistance of 12 mm Weldox 700 steel targets with gas gun fired ogival projectiles which have 52 HRc hardness. Although comprehensive strength and failure models were given for armor plate, hardened steel projectile was modeled as an elastic–plastic material with bilinear isotropic hardening without fracture [13,15]. Fountzoulas et al. [18] studied tungsten carbide sphere impact on HSLA-100 including both SPH and Lagrange methods and conclude that Lagrange is more successful in steel target modeling. A similar outcome for SPH also derived by Buyuk et al. [19] In their study deformation pattern of thin aluminum folio against 9 mm Nato ball bullet was studied both experimentally and numerically. SPH results were found to be similar in behavior but poor in magnitude. Mostly, SPH methodology is used to model ceramic targets in ballistic simulation due to its enhanced sensitivity to spall formation.

In this paper, ballistic limit thickness for Secure 500 was determined against 7.62 mm 54R B32 API hardened steel core ammunition using both Lagrange and smoothed particle hydrodynamics SPH simulations. The parameters related with numerical modeling such as mesh size, contact algorithms are validated with perforation tests on 9 and 20 mm thickness. Also material tests were performed for armor steel and ammunition hardened steel core to develop Johnson–Cook constitutive relations for both strength and failure models. Material data for the bullet jacket and sabot were mainly taken from literature. Finally, results from 3D numerical simulations with detailed models of bullet and target were tabulated to find minimum ballistic thickness against Stanag 4569 level 3 threats.

2. Material behavior and modeling

In order to describe multiple physical phenomena taking place during high velocity impact and penetration, it is required to characterize the behavior of materials under high strain rate loading conditions. The material behavior model includes not only the stress–strain relationship at large strains or different strain rates but also accumulation of damage and mode of failure. Such complex material behavior including fracture is difficult to characterize in analytical models but in numerical simulations, complex constitutive materials models can be implemented. A widely used material model in ballistic penetration studies which also available in commercial hydro-codes is Johnson–Cook. The Johnson–Cook model is a visco–plastic model for ductile metals that consider strain hardening, strain rate and thermal softening effects on material behavior and fracture [20]. This model is widely used since its first publication in 1983. For many materials, J–C parameters can be easily found in open literature. In spite of parameters availability for many materials, when ballistic application is the subject of study, not a lot of publications give their material parameters or share rather general parameters taken from open literature. For this reason, in the characterization of materials for simulation, deriving experiment based models is crucial part of the study.

Johson–Cook expresses the equivalent stress as a function of plastic strain, strain rate and temperature with an empirical relationship for the flow stress, which is represented as [20].

$$\sigma_Y = \left[A + B\varepsilon_p^n\right]\left[1 + C\log\dot{\varepsilon}_p^*\right]\left[1 - T_H^m\right] \tag{1}$$

where ε_p is the equivalent plastic strain, $\dot{\varepsilon}_p^*$ is the dimensionless plastic strain rate for $\dot{\varepsilon}_0$, T_H is homologous temperature $\{T_H = (T - T_{\mathrm{room}})/(T_{\mathrm{melting}} - T_{\mathrm{room}})\}$. The five material constants are A, B, C, n and m. The expression in the first set of brackets gives the stress as a function of $\dot{\varepsilon}_p^* = 1$ and $T_H = 0$. The expression in the second and third sets of brackets represent the affects of strain rate and thermal softening respectively.

In order to describe ductile fracture, Johnson and Cook also proposed a model including the effects of stress triaxiality, temperature, strain rate on failure strain. The Johnson–Cook damage model is a cumulative damage – fracture model that takes into account the loading history, which is represented by the strain to fracture. In other words, model assumes that damage accumulates in the material during plastic straining and the material breaks immediately when the damage reaches a critical value. This means the damage has no contribution on the stress field until the fracture happens. The strain to fracture is expressed as a function of strain rate, temperature and pressure. Parameters of strain hardening D_1,D_2 and D_3 are predominant compared with two others strain rate hardening and thermal softening, therefore should be found out carefully. J–C is an instantaneous failure model, which means no strength remains after erosion of an element. The damage of an element is defined on a cumulative damage law:

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon^f} \tag{2}$$

in which

$$\varepsilon^f = \left[D_1 + D_2\exp(D_3\sigma^*)\right]\left\lfloor 1 + D_4\ln|\dot{\varepsilon}_p^*|\right\rfloor\left[1 + D_5 T_H\right] \tag{3}$$

The dimensionless pressure/stress ratio (σ^* is the ratio of hydrostatic stress per effective stress) is a measure of triaxiality of the stress state and defined as

$$\sigma^* = \frac{\sigma_H}{\sigma_{eq}} = \frac{(\sigma_x + \sigma_y + \sigma_z)/3}{\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x\sigma_y - \sigma_y\sigma_z - \sigma_z\sigma_x + 3(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)}} \tag{4}$$

The damage variable D take values between 0 and 1, here $D = 0$ for an undamaged material and failure of the elements assumed to occur when $D = 1$. The failure strain and thus the accumulation of damage is a function of mean stress, strain rate and temperature.

2.1. Armor plates

The armor material used in ballistic tests is an alloyed, liquid-quenched and tempered high-strength special steel for civil use which has 500 HB hardness. The material properties tabulated for transverse specimens according to EN 10002 in Table 1.

The data obtained from laboratory tests are grouped in two types. First test series consisted of the quasi-static tests at large strains performed at room temperature. Four various strain rates were performed 10^{-4}, 10^{-3}, 10^{-2} and 0.1 s^{-1} on two type smooth flat specimens taking length to cross section ratio as 2. All the tensile