Penetration of steel plates by long ceramic rods

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ABSTRACT

We have studied the penetration/perforation of rigidly clamped circular steel plates by high kinetic energy AD-85 ceramic rods. The ceramic is modeled as an elastic/plastic material with pressure cut-off and the steel is modeled as a linearly strain-hardening elastic/plastic material with the failure strain dependent upon the strain-rate. The effect of frictional force at the target/penetrator interface is accounted for, and failed elements are removed from the analysis. Whereas for low impact speeds, the ceramic rod fails causing some damage to the steel plate, at higher impact speeds, the ceramic rod perforates through the steel plate. The effect of the nose shape of the rod on the efficiency of penetration has been delineated.

1. INTRODUCTION

During dynamic deformations, the commercial AD-85 alumina has been shown to exhibit the following features [1-5]: (i) the loss of shear strength during shock loading, (ii) reduction of the spall strength with an increase in the intensity of the compression shock, (iii) multiple microcracking, (iv) viscous flow associated with local melting, (v) the residual spall strength after passage of the compressive wave is a function of the initial impact speed, (vi) the strength of ceramics is quite high under shock loading, and (vii) the Hugoniot elastic limit of ceramics (~6-10 GPa) is very high as compared to that of high strength metallic alloys (~1-3 GPa). Good fracture toughness and high Hugoniot elastic limit of ceramics make them good candidates for kinetic energy penetrators. Here we show that indeed ceramic rods can perforate steel plates at moderate impact speeds.

2. FORMULATION OF THE PROBLEM

We assume that a ceramic cylindrical rod impacts at normal incidence a circular steel plate rigidly clamped at its periphery and the axis of symmetry of the two stay coincident throughout the penetration process. The deformations of the rod and the plate are taken to be axisymmetric. Even though an impact problem may involve high temperature rise of material points adjacent to the target/penetrator interface, the dependence of material
properties upon the temperature has been neglected and a mechanical problem is analysed herein. The problem is formulated in the referential description of motion. Equations expressing the balance of mass and linear momentum may be found in Truesdell and Noi1 [6].

The steel is modeled as an elastic/plastic material with linear strain-hardening. An element is assumed to fail when the effective plastic strain in it equals a prescribed value and failed elements are eliminated from the analysis. The AD-85 alumina is modeled as an elastic/plastic material with the dynamic yield stress increasing affinely with the compressive hydrostatic pressure. Values of the Hugoniot elastic limit, the quasistatic yield stress and the pressure-volumetric strain relation are different in compression and tension; the reader is referred to Flocker and Batra [7] for details of these relationships. A ceramic material point is assumed to fail when the hydrostatic pressure there is tensile and its magnitude exceeds the spall strength of the material. At the target/penetrator interface we impose the condition of impenetrability and assume that the dynamic coefficient of friction, \( \mu \), is given by \( \mu = \mu_k + (\mu_s - \mu_k) e^{-\gamma v_{rel}} \) where \( \mu_s \) and \( \mu_k \) are the static and kinetic coefficients of friction respectively, \( \gamma \) is a transition coefficient and \( v_{rel} \) is the relative speed between the two sliding surfaces. All bounding surfaces of the penetrator except the target/penetrator interface are traction free. The target plate is assumed to be rigidly clamped at its periphery and other surfaces except the target/penetrator interface are taken to be traction free.

Initially the target particles are at rest and are unstressed, and the penetrator particles are unstressed and are moving in the axial direction with a uniform speed \( V_0 \).

3. RESULTS AND DISCUSSION

The problem stated above is both geometrically and materially nonlinear. We seek its approximate solution by the finite element method and use the explicit general purpose code DYNA2D [8]. As is clear from Fig. 1, both the penetrator and the target are divided into uniform rectangular elements. The deforming regions are rezoned after some of the elements have failed and/or other elements have been severely deformed. The slideline algorithm is used to satisfy the condition of non-interpenetration at the target/penetrator interface.

Values assigned to material parameters for the AD-85 ceramic [9,10] and the 4340 steel are as follows. AD-85 ceramic: Poisson's ratio = 0.22, Mie Gruniesen parameter = 1.0, initial mass density = 3420 kg/m³, shear modulus = 108 GPa, static tensile yield stress = 155 MPa, static compressive yield stress = 1930 MPa, spall strength = 400 MPa, elastic unloading bulk modulus = 186 GPa, Hugoniot elastic limit in compression = 6 GPa;

4340 steel: Young's modulus = 200 GPa, Poisson's ratio = 0.29, yield stress = 970 MPa, tangent modulus = 470 MPa, effective plastic strain at failure = 0.77, mass density = 7850 kg/m³.

Figures 2 and 3 depict, for several values of time \( t \), the deformed configurations of the ceramic penetrator and the steel plate for impact speeds of 3 km/s and 5 km/s. Just after impact high intensity stress waves propagate into the rod and the target and cratering of the plate surface and penetration of the rod commence immediately. In each case the
steel plate is perforated; as expected the perforation time is less for an impact speed of 5 km/s as compared to that for the ceramic rod moving at 3 km/s. In both cases, the ceramic near the outer surface of the rod and close to the impacted end fails, making the penetrator nose somewhat pointed. There is a small crater formed in the steel plate and the penetrator nose gets eroded giving rise to a gap between the penetrator and the target. Multiple impacts occur between the rod and the plate, the number of impacts depends upon the initial velocity of the rod, the crater continues to enlarge, the plate is eventually perforated and essentially all of the penetrator is destroyed. The shape of the hole formed in the plate at the instant the rod just exits the plate is different in the two cases; however, because of the kinetic and elastic energy imparted to the plate, the hole continues to grow even after the rod has exited the plate.

At an impact speed of 0.5 km/s, the steel plate was not perforated [11]. Initially, the inner portion of the ceramic rod close to the axis of symmetry failed, subsequently the portion of the ceramic rod near the target/penetrator interface buckled because of the high resistance to penetration offered by the strong and dense steel. Even though the plate was bent, no noticeable crater formed in the plate.

In Fig. 4 we have plotted the initial and deformed configurations of the ceramic rod and the steel plate when the rod has an ogive nose and the impact speed equals 3 km/s. The shank diameter and the length of the ceramic rod with the pointed nose equal 10.43
Fig. Flat nosed AD-85 ceramic penetrator and 4340 steel target. Impact velocity: 3 km/s.
Fig. 3 Flat nosed AD-85 ceramic penetrator and 4340 steel target. Impact velocity: 5 km/s.
Fig. 4 Ogive nosed AD-85 ceramic penetrator and 4340 steel target. Impact velocity: 3 km/s.
mm and 52.15 mm respectively whereas those for the flat-nosed penetrator were 10 mm and 50 mm. However, the volume and hence mass of the ceramic penetrator in the two cases will be the same. As expected, elements near the pointed nose of the penetrator fail first because of the compressive waves reflected as tensile waves from the free surfaces. At $t = 4.39 \mu s$ most of the pointed nose has been eroded away and there is a gap formed between the rod and the plate. Multiple impacts result in further erosion of the rod material near its axis of symmetry and the failure zone spreads outwards. Eventually the entire rod is eroded away and a paraboloid shaped crater is formed in the steel plate.

CONCLUSIONS

We have studied the axisymmetric penetration of a ceramic rod into a circular 4340 steel plate rigidly clamped at its edges. For flat nosed ceramic rods, the nose shape was initially deformed into conical. Subsequently the conical part failed resulting in a smaller flat-nosed rod. It was followed by a failure of the rod material near its axis of symmetry and the front end thus forming a cutting edge. Multiple impacts between the rod and the crater formed in the plate eventually perforated it.

Whereas a flat-nosed ceramic rod traveling at 2 km/s perforated a hole in the steel plate [11], the pointed-nosed rod of the same mass formed only a crater in the plate suggesting that a flat-nosed penetrator has a better penetration efficiency. For rigid penetrators and thermoviscoplastic targets, Batra [12] found that flat nosed penetrators resulted in deformations of the target over a wider region as compared to hemispherical and ellipsoidal nosed penetrators.

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