NUMERICAL ANALYSIS OF THE DYNAMIC FRACTURE IN LAYERED METAL/CERAMIC TARGETS UNDER IMPACT LOADING

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The present paper deals with the analytical and numerical modelling of the mechanical behaviour and fracture of metals and ceramics subjected to projectile impact at medium and high velocities. Analytical modelling is made by dividing the perforation process in different penetration stages and applying basic theorems of the Plasticity Theory. Numerical modelling is performed by means of a computer program, based on the finite difference method with explicit time integration scheme, for the full numerical analysis of dynamic problems involving contact or impact. The results obtained by both methodologies for some particular situations are compared with the corresponding experimental observations, with remarkable agreement between all of them.

INTRODUCTION

In dealing with impact problems it is neccesary to take into account a set of particular phenomena, such as material thermo-viscoplastic behaviour at high strain rates and the fracture and erosion behaviour of both the target and the projectile.

The first analytical models used to predict the response of a particular material subjected to impact loading, were of a mainly empirical nature. In 1983, Ravid and Bodner [1] proposed a self-contained analytical model in which the perforation process is divided into five different stages, corresponding to different succesive mechanisms for the mechanical response of the impacted plate. In such model, a rigid projectile is supposed to collide with a rigid-viscoplastic plate. Different rupture criteria are considered in the model, such as adiabatic shearing, macroscopic ductile failure,etc. In each penetration stage, an appropriate velocity field verifying the incompressibility condition is assumed. Then an upper bound theorem of the Plasticity Theory incorporating inertia terms as previously stated by Tirosh and Kobayashi [2] is applied. As a result, the total energy rate required to deform the target material can be estimated, thus allowing an evaluation of the forces acting on the projectile.

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For impact velocities higher than say 1000 m/s, the perforation process is more complicated: different phenomena such as shock waves and erosion effects appear in both projectile and target. In this case additional stages must be incorporated to the penetration model. Recently, Ravid et al. [3], by following the same philosophy as the previous model of Ravid and Bodner [1], have developed a new initial stage for such model taking into account shock wave propagation and stress release due to rarefaction waves. Moreover, an analytical model taking into account projectile erosion effects associated with penetration processes was presented by Tate [4], which has become a standard reference in the high velocity regime. Recently, Jones et al. [5] have suggested a modification of that model to account for the strain at the tip of the projectile due to mushrooming.

For the case of mixed and layered armour (ceramic plus metallic backing plate), Ravid et al.[6] have presented a new model that considers different additional penetration stages before the projectile reaches the metallic plate: an initial impact stage where the effect of shock waves is important, a ceramic erosion stage, a stage of penetration in broken ceramic, and another stage where the backing of the metallic plate contributes to the target resistance to projectile motion.

This paper presents an analytical model based on the previous ones, with particular emphasis on the erosion phenomena of both the projectile and the target. This model divides the penetration process into seven different stages. The results obtained by employing this model are compared with those obtained by a full numerical analysis of the same problems or with experimental or numerical information taken from the literature.

ANALYTICAL MODEL

The model presented here for the penetration of metal/ceramic layered armours by cylindrical projectiles, consists of seven different stages. Firstly, an initial stage is considered in which the shock wave phenomena indicated are taken into account. This part of the model is a direct application of the model of Ravid et al. [3].This stage terminates when rarefaction waves produced at the free boundaries of the projectile reach the shock wave front. The elapsed time in this process is a very few micro-seconds. The main influences of this stage in the penetration process are:

a) the linear momentum of the projectile decreases because the projectile-target interface is moving to a speed lower than that of the unaffected projectile, which continues moving at the initial impact velocity. The velocity field in the affected region of the projectile is considered linear.

b) some parts of the projectile have broken because a limit strain has been reached and, consequently, they are not able to support shear stresses any more. Additionally, the tip of the projectile takes a mushroomed shape and thus a projectile mass separates from the projectile body and it is ejected backwards.

The equation that governs this stage is:

$$\dot{\mathbf{W}}_p = \dot{\mathbf{W}}_t \qquad (1)$$

where $\dot{\mathbf{W}}_p$ and $\dot{\mathbf{W}}_t$ are the work rates in both projectile and target.

Then the erosion stage begins, and such effect plays the main role in the penetration process. The model adopted for this phase is mainly that due to Tate [4] in the modified form presented by Jones et al. [5], in order to account for the mushrooming strain produced at the tip of the projectile. The basic equations (see Section of Symbols Used for better understanding) of this model are:

$$\mathbf{l}\ \dot{\mathbf{v}} + \dot{\mathbf{l}}\ (\mathbf{v}-\mathbf{u}) = -\ \mathbf{p}\ /\ (\ \rho\ (\ \mathbf{1}+\mathbf{e}\ )\ ) \qquad (2)$$

$$\mathbf{e}\ \dot{\mathbf{l}} = \mathbf{v} - \mathbf{u} \qquad (3)$$

$$\mathbf{p} = 1/2\ \mu^2\ \rho\ \mathbf{u}^2 + \mathbf{R} = 1/2\ \rho\ (\mathbf{v}-\mathbf{u})^2 + \mathbf{Y} \qquad (4)$$

Jones et al. [5] have shown the large influence of the value of the engineering strain **e** in the result of the penetration process. They have also proposed that the appropriate value should be estimated previously from the experimental value of the crater diameter produced in the target.

On account of the influence of the paramenter **e** in the model, it is convenient to establish the range of variation of such value to obtain reliable results. From Eq. (2) it is evident that the minimum value of **e** becomes -1.0. Values of **e** less than -1.0 would not be physically possible in this problem. Values of **e** near zero, but negative, would lead (see Eq. (3)) to an unreallistic large projectile erosion rate. In these conditions a critical value of the strain **e** may be defined, and it corresponds to zero acceleration in the projectile. From Eq. (2) ,

$$\mathbf{e}_{\mathbf{critical}} = -\ 1\ /\ (\ 1 + \mathbf{p}\ /\ (\ \rho\ (\mathbf{v} - \mathbf{u})^2\ )\ ) \qquad (5)$$

and thus **e** varies between -1.0 and the critical value given by Eq. (5).

The above hydrodynamic model of Tate applies to semi-infinite targets, and consequently its use in moderately thick targets is not straightforward. In effect, ceramic fracture near the rear surface of the ceramic plate due to rarefaction waves at the metal/ceramic interface greatly complicates the problem. The model of Ravid et al. [6], for impact on layered ceramic/metal target considers this latter circumstance. In fact, in stage three of their model, Ravid et al. [6] consider that the projectile is moving into fragmented ceramic providing a strength of about twenty per cent of the intact ceramic strength. Such value is taken on the basis of some limited tests on constrained fragmented ceramic samples (see Ravid et al. [6]). In the model proposed in this paper, and considering that projectile advance is firstly produced through intact and, latter, fragmented ceramic media, a weighted average of the ceramic strength is taken in order to obtain a proper representative value of that parameter. This indetermination in the exact value of the ceramic strength must be kept in mind when interpreting the results of the analyses.

The erosion stage terminates when the projectile reaches the ceramic/metal interface. Then, the perforation of the metallic plate begins. This latter process can be modelled by using the well known model of five stages proposed by Ravid and Bodner [1].

APPLICATIONS

The first case to be analyzed corresponds to the impact of a 12.7 mm diameter hard-steel projectile with a 60 deg conical tip, having an average mass of 30 g, on a 6.35 mm thickness alumina AD85 backed by a SAE 4130 steel plate of the same thickness. The impact velocity is 650 m/s. For this case experimental evidence [7] shows that arrest of the projectile may be expected with a reduction of about 12 mm in its length due to erosive processes in the ceramic plate. The standard properties of the materials involved have been taken from references [8,9]. Two alternative analyses of such a problem have been carried out using the seven stage model and a full numerical analysis by means of a computer code based on the finite difference method.

In Fig.1(a), the projectile velocity corresponding to the instant when the projectile reaches the ceramic/target interface is plotted as a function of the target-strength/projectile-strength ratio. In Fig. 1(b) the reduction of the projectile length is also plotted as a function of such ratio. Moreover, in Fig. 2 the time histories of the linear momentum of the projectile obtained by both the analytical model and the full numerical analysis are depicted. A good agreement between them is observed.

The proposed model has also been tested in the case of a AP M2 projectile (5.3 g mass) impacting a ceramic/target armour plate (AD 90 +Al 7017) at an initial velocity of 830 m/s. It is found in [6] that for a 7 mm AD 90 + 9.5 mm Al 7017 plates, the projectile reaches the metal/ceramic interface at a velocity of 554 m/s, having a corresponding reduction length of 2 mm. On the other hand, the model proposed here gives values of 554 m/s and 5.6 mm, respectively. For the case of a 9.5 mm AD 90 + 6.35 Al 7017 plates, values of the interface velocity of 389 m/s and of the length reduction of 3 mm are calculated in [6], whereas the present model gives 475 m/s and 6.6 mm, respectively. Although in this latter case a 20 % difference in the projectile velocity at the interface is encountered, it is found that both models predict fairly well the same total linear momentum for the projectile.

CONCLUSIONS

The model for impact of a cylindrical projectile on a layered ceramic-metal target plate proposed in this paper gives results which compare well, in the range of impact velocities considered, with those obtained by means of a full numerical analysis of the same problems, as well as with other results available in the literature. However, some degree of indetermination exists in the values of the mushrooming strain and the fragmented ceramic strength to be used in the model. This suggests the need for further work to increase the understanding of such effects.

SYMBOLS USED

e = engineering strain at the tip of the projectile (mushrooming strain)
l = remaining undeformed length of the projectile
v = initial impact velocity of the projectile
u = interface projectile-target velocity
p = interface projectile-target pressure
ρ = mass density of the projectile
μ^2 = ratio of mass density of target to that of the projectile
R = target strength
Y = projectile strength

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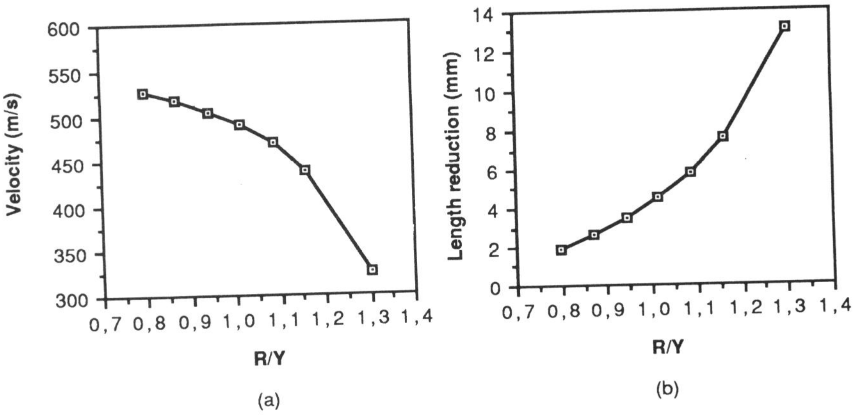

(a) (b)

Figure 1 Velocity of projectile at the metal/ceramic interface and projectile length reduction for different R/Y ratios.

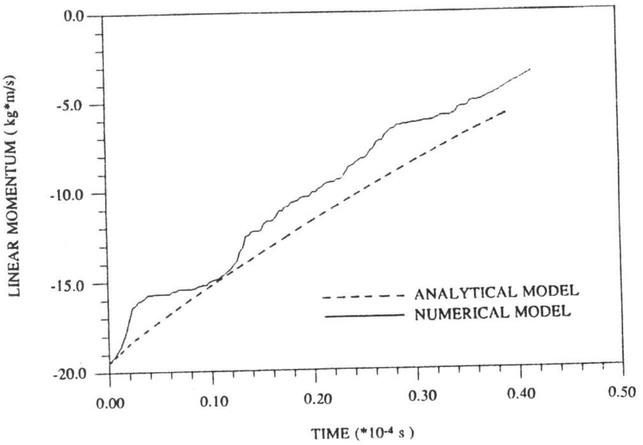

Figure 2 Time histories of the linear momentum of the projectile.