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Theoretical analysis of projectile-target interface defeat and transition to penetration by long rods due to oblique impacts of ceramic targets

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ABSTRACT

Integrated with related investigations, the present manuscript conducts systematical theoretical analysis on the interface defeat (the phenomenon where an impacting eroding projectile flows radially outward along the surface of target without any significant penetration) of long rods under the oblique impacts onto ceramic targets, and related comparison with the normal impact is also carried out. By taking the influence of obliquity angle into account, the corresponding formulae for the velocity decay and the mass erosion of long rods with time are deduced out, and the kinetic energy loss is further discussed. Moreover, the transition from interface defeat to penetration is analyzed in detail. The variation characteristic of critical impact velocity range with the increase of obliquity angle is discussed, and the critical transition time is deduced considering the damage and failure characteristics of the ceramic target. Furthermore, the corresponding theoretical expressions are formulated. Finally, some suggestions for optimizing the design of ceramic target are given based on related analysis.

1. Introduction

Since it is first reported by Hauver and his colleagues [1–5], interface defeat (or called dwelling) of long rods on the ceramic targets, i.e., the impacting rod is forced to flow radially outwards along the target surface without significant penetration, has been studied extensively in the last two decades. Beside Hauver et al.'s systematical investigations [1–5], Rosenberg's group [6–11], Orphal's group [12–15], Anderson and Behner's group [16–30] and Lundberg's group [31–38] also conducted numerous researches on the impact onto ceramic targets, involving the interface defeat and the direct penetration, etc. In addition, many numerical investigations are also implemented [39–43], and recently the authors also conducted detailed theoretical analysis on the interface defeat and the transition phenomenon from interface defeat to penetration under the normal impact condition [44,45].

In the practical engineering application, the ceramic armor on the tank or the panzer is usually installed obliquely to disperse the pressure derived from the impact of long rods or even to induce the deflection of rods. Consequently, a large amount of investigations on the oblique impacts of long rods onto ceramic targets are also conducted [5,11,17,28,29,46–51]. Among these researches, Hauver et al. [5] and Anderson et al. [28,29]'s tests found that for the oblique impacts of the tungsten (W) and gold (Au) long rods onto ceramic targets, various ballistic performances, including interface defeat, direct penetration and transition from interface defeat to penetration, also occurred within different impact velocity ranges. Besides, compared with the case under the normal impact, the lower bound of critical impact velocity range (below this bound the rod is forced to behave as interface defeat only) increases significantly, i.e., the protective capability of the ceramic target achieves remarkable improvement under the oblique impact.

During the interface defeat process, mass erosion occurs in the long rod due to that its nose flows radially outwards, and the rod velocity will decrease gradually because of the resistance derived from the target. Consequently, the rod will lose its kinetic energy, and this further decreases its penetrating capability into the target. As aforementioned, the interface defeat characteristic of long rods under the oblique impact is considerably different with that under the normal impact, and thus it can be inferred that the velocity decay, mass erosion and kinetic energy loss of the rod may behave as different patterns from the cases under the normal impact, and the impact pressure on the target surface and the damage and failure within the ceramic target would also be quite different.

Based on the authors' previous theoretical research [44,45] and integrated with related investigations, theoretical analysis on the interface defeat and the transition from interface defeat to penetration for the long rod which impacts obliquely onto the ceramic target is further conducted in the present manuscript. Variations of the

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rod velocity, rod mass and kinetic energy for the long rod are discussed in detail. The variation of critical impact velocity range with increasing the obliquity angle and the corresponding critical transition time are analyzed, and related theoretical expressions are formulated. Moreover, comparisons of the rod and target performances between the oblique impact and the normal impact are also conducted. Besides, it is worthy to note that all rods in related investigations mentioned above are flat-nosed (cylindrical) long rods, and for the convenience of deducing the corresponding formula, the analysis in the present manuscript will focus on the flat-nosed long rod.

2. Velocity decay and mass erosion of the long rod

Hauver et al. [5] and Anderson et al. [28,29]'s tests demonstrated that during the oblique interface defeat materials within the rod nose also behave as a steady radial flow. Fig. 1 lists the typical deformation and failure patterns of the rod and the target for different kinds of long rods under different obliquity angles θ and impact velocities v_0 [5,28,29], wherein the front surface of ceramic target in Fig. 1(a) is covered with a buffer and that in Fig. 1(b) is bare. It is seen that due to the asymmetrical action of the oblique target surface, the flow of rod material almost shows a fan pattern on the surface along the direction of decreasing target length, whereas not behaves as symmetrical flow like the case under the normal impact. Nevertheless, the corresponding flow and the consequent rod erosion are still relatively steady.

The status of interface defeat of long rods under the normal and oblique impacts can be sketched in Fig. 2, wherein R is the rod radii; l is the eroded length and l' the residual length, $l'+l=l_0$, in which l_0 stands for the initial rod length. From Fig. 2 it can be seen that under the oblique impact condition, the interface between the rod and the target becomes to an elliptical shape from the circular surface in the normal impact condition (the initial stage of impact is ignored), and the corresponding major axis is $R/\cos\theta$. Hence, the mass erosion and the velocity decay of the rod during the interface defeat would differ considerably from the cases under the normal impact.

Based on the modified Bernoulli equations used for the long rod penetration [52,53], the authors further deduced the govern equations for the interface defeat of the flat-nosed long rod under the normal impact condition [44]

$$\left(M-\rho_p\pi R^2 l\right)v\frac{dv}{dl}=-\sigma_{yp}\pi R^2 \tag{1}$$

$$\frac{dl}{dt}=v \tag{2}$$

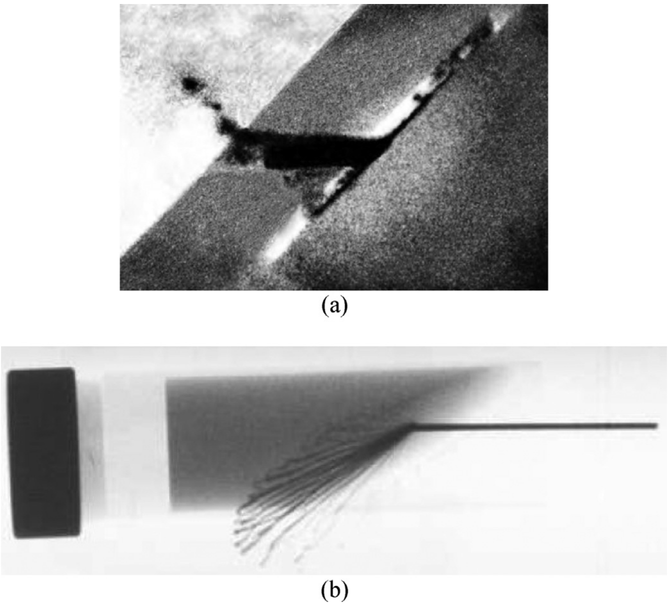

Fig. 1. Interface defeat of long rod under the oblique impact onto ceramic targets: (a) Tungsten (W) rod, TiB_2 target, v_0=1600 m/s, θ=45° [5], (b) Gold (Au) rod, SiC-N target, v_0=1067 m/s, θ=60° [28,29].

In Eqs. (1-2), M stands for the initial mass of the long rod; ρ_p and σ_{yp} are the density and the dynamic yield strength of the rod material, respectively; v is the rod velocity (tail velocity). l and v are both functions of time t, and when $t=0$, $l=0$ and $v=v_0$.

From Fig. 2 it can be seen that for the oblique impact, corresponding to the eroded length l, the height of the eroded oblique elliptical truncated cone is $h=l\cos\theta$. Consequently its volume can be calculated as $\pi R(R/\cos\theta)h=\pi R(R/\cos\theta)l\cos\theta=\pi R^2 l$, and thus it can be known that the eroded mass is $\rho_p\pi R^2 l$. Hence, under the oblique impact, Eq. (1) becomes

$$\left(M-\rho_p\pi R^2 l\right)v\frac{dv}{dl}=-\sigma_{yp}\pi R\frac{R}{\cos\theta} \tag{3}$$

By deducing Eq. (3) it can be obtained

$$\frac{1}{2}\rho_p\left(v^2-v_0^2\right)=\frac{1}{\cos\theta}\sigma_{yp}\ln\left(1-\frac{\rho_p\pi R^2 l}{M}\right) \tag{4}$$

Thus, the relationship between the residual length l and the rod velocity v can be further obtained as

$$l=\frac{M}{\rho_p\pi R^2}\left\{1-\exp\left[\frac{\rho_p}{2\sigma_{yp}}\left(v^2-v_0^2\right)\cos\theta\right]\right\} \tag{5}$$

Substitute Eq. (5) into Eq. (3) again, and by integrating with Eq. (2) it yields

$$dt=-\frac{M}{\pi R^2\sigma_{yp}}\cos\theta\exp\left[\frac{\rho_p}{2\sigma_{yp}}\left(v^2-v_0^2\right)\cos\theta\right]dv \tag{6}$$

Similar to our previous analysis [44,45], define a constant parameter K (with dimension of [T]) and a dimensionless constant A as

$$K=\frac{Mv_0}{\pi R^2\sigma_{yp}} \tag{7a}$$

$$A=\frac{\rho_p v_0^2}{2\sigma_{yp}} \tag{7b}$$

By integrating the both sides of Eq. (6) the rod velocity v as a function of time t can be expressed as

$$t=K\cos\theta\cdot\exp(-A\cos\theta)\cdot\int_{v/v_0}^{1}\exp\left[A\cos\theta\left(\frac{v}{v_0}\right)^2\right]d\frac{v}{v_0} \tag{8}$$

Comparatively, the corresponding formula under the normal impact condition is deduced as [44,45]

$$t=K\exp(-A)\cdot\int_{v/v_0}^{1}\exp\left(A\left(\frac{v}{v_0}\right)^2\right)d\frac{v}{v_0} \tag{9}$$

By comparing Eq. (8) with Eq. (9) it can be found that they have the similar expression forms. However, a factor $\cos\theta$ is introduced into the coefficient in Eq. (8), and it means that the obliquity angle has a significant influence on the velocity decay of the rod.

As the integration term in Eqs. (8) and (9) shows as a form of $\int\exp\left(x^2\right)dx$, one can't get its analytical solution, and alternatively the variation of rod velocity v with time t could be solved numerically [44,45]. Then the variation of the eroded length l can be further obtained based on Eq. (5), and finally the mass erosion of the rod can be calculated.

As the authors mentioned before [44,45], in the practical engineering application it is necessary to make some reasonable simplification under the assurance of correct prediction and further give the explicit analytical relationships with time t. The motion of the long rod is quasi-steady during the interface defeat, and the decay of rod velocity v is small; besides, the velocity decay shows an approximate