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On the transition from interface defeat to penetration in the impact of long rod onto ceramic targets

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A B S T R A C T

Based on the related research on the penetration of long rod into ceramic targets, the present manuscript summarizes qualitatively three deformation modes of the rod and target under different impact velocities: interface defeat, normal penetration and transition from interface defeat to penetration. Then the phenomenon of transition is investigated in detail. Firstly, integrated with the analysis on the mechanical property of ceramic material, the critical impact velocity range within which the transition phenomenon occurs, i.e., the highest impact velocity corresponding to interface defeat and the lowest impact velocity corresponding to normal penetration, is further identified. Subsequently, the critical transition time from interface defeat to penetration is discussed, in which the detailed damage and failure characteristics of ceramic material during the interface defeat process are taken into account. Finally an explicit half-analytical expression of the critical transition time is formulated.

1. Introduction

Interface defeat in the ceramic targets, i.e., the impacting rod is forced to flow radially outwards along the surface of target without significant penetration, has been studied extensively in the last two decades. This phenomenon was first reported by Hauver and his colleagues [1–5], and then Rosenberg's group [6–9], Orphal's group [10–13], Lundberg's group [14–21] and Anderson's group [22–33] conducted a large amount of investigations on the impact onto ceramic targets, involving the interface defeat and the normal penetration, etc. Besides, Holmquist and Johnson also conducted related numerical investigations [34–37], and the authors also conducted detailed theoretical analysis on the interface defeat recently [38,39]. The corresponding work includes experimental investigation, theoretical analysis and numerical simulation.

Among the above research, Lundberg et al. [14] conducted lots of impact experiments onto various ceramic targets for tungsten (W) and molybdenum (Mo) long rods, and found that when the impact velocity v_0 is below a certain lower threshold value, only interface defeat occurs and the rod can not penetrate into the target; Comparatively, when v_0 exceeds an upper threshold value, the rod penetrates into the target directly without interface defeat; While v_0 locates within this critical impact velocity range, interface defeat occurs and lasts for a certain duration firstly, and then the rod further penetrates into the target gradually. These phenomena is also found in Westerling et al. [16]'s experiments, in which the tungsten rod impacted onto the confined ceramic target at $v_0 = 1454$ m/s, interface defeat occurred first and lasted for about 15.7 μs, then the rod penetrated into the target. The corresponding impact process is shown in Fig. 1. Anderson et al.'s tests and numerical simulations also demonstrated the similar deformation characteristics [24,28,30,32].

Lundberg et al. [14] suggested a possible range of the axisymmetric pressure of projectile load within which the transition phenomenon would occur, and thus the corresponding critical impact velocity range can be further obtained. Besides, Lundberg et al. and Anderson et al.'s experiments further demonstrated that the critical impact velocity range may be relatively narrow, even the critical impact velocity may take as a unique value [18,30,32]. Recently, Lundberg et al. [21] further investigated the influence of length scale on the transition features, and found that when the length scales of rod and target are small (e.g., the projectile radius $r < 0.5$ mm and the target radius $R < 5$ mm), both the length scale and the mechanical property of ceramic material affect significantly the critical impact velocity; Comparatively, for the relatively larger length scale, the critical impact velocity mainly depends on the property of ceramic material.

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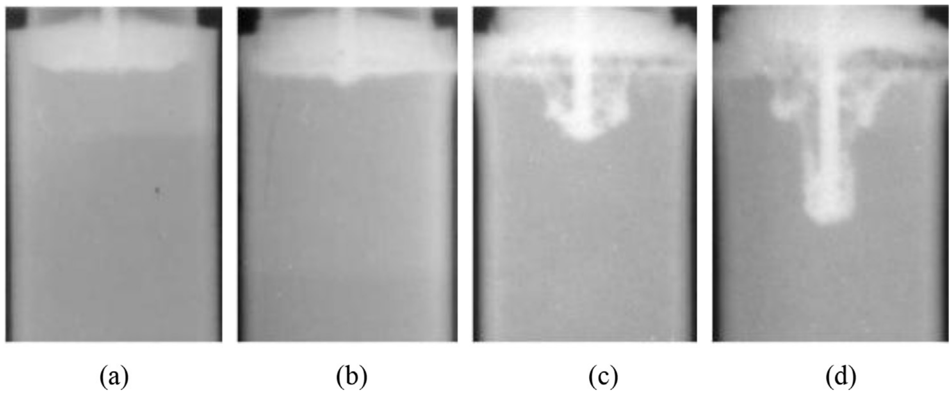

Fig. 1. Impact process of a tungsten long rod onto ceramic target at $v_0 = 1454$ m/s, Ref. [16]: (a) t = 9.5 μs, (b) t = 15.7 μs, (c) t = 36.4 μs, (d) t = 46.4 μs.

Based on the related research, three deformation modes of the long rod and the ceramic target under different impact velocities are summarized qualitatively, and the corresponding variation characteristics of rod velocity in different modes is distinguished. Then the critical impact velocity range within which the transition from interface defeat to penetration occurs is further modified after Lundberg et al.'s work [14,21]. In the end, the transition phenomenon is investigated in detail, especially the critical transition time t_c is analyzed based on the damage and failure characteristics of ceramic material, and a half-analytical approximate expression is formulated. The corresponding analytical expression is convenient for the engineering application under the assurance of reasonable prediction. Besides, it should be noted that related analysis in the present manuscript mainly focuses on the case with relatively large length scales of rod and target, i.e., the scaling effect will not be considered.

2. Three deformation modes in the impact of long rod onto ceramic targets

From the aforementioned research [1–39] it can be found that when the impact velocity v_0 is below the lower bound of critical impact velocity v_0^{lower}, only interface defeat occurs during the impact process, and the nose velocity of long rod is almost zero; When v_0 exceeds the upper bound of critical impact velocity v_0^{upper}, the long rod behaves as a normal penetration and its motion obeys the Alekseevski–Tate model [40,41]; Comparatively, if the impact velocity locates within these two bounds, i.e., $v_0^{lower} < v_0 < v_0^{upper}$, the long rod will behave as interface defeat firstly and then begins to penetrate into the target after a certain duration. The variation characteristics of the nose and tail velocities of the rod under the three deformation modes can be qualitatively represented in Fig. 2.

Some practical validations for the above conclusions are Anderson and Walker [24]'s numerical simulations for the small arms projectile impacting onto ceramic/metal target and Walker [23], Chocron et al. [27] and Reaugh et al. [42]'s simulations for the long rod penetration. In Anderson and Walker [24]'s simulations, when the small arms projectile impacts onto the target at $v_0 = 701$ m/s and 820 m/s, respectively, interface defeat occurs in the early stage and lasts for about 20 μs before the projectile begins to penetrate into the target. It is found that during the interface defeat, the nose velocity of projectile is indeed very low and almost equals to zero. Moreover, the variation characteristics of the nose and tail velocities are similar to that in Fig. 2(b). In Walker [23], Chocron et al. [27] and Reaugh et al. [42]'s simulations, the tungsten long rods penetrate into the thick ceramic targets directly at

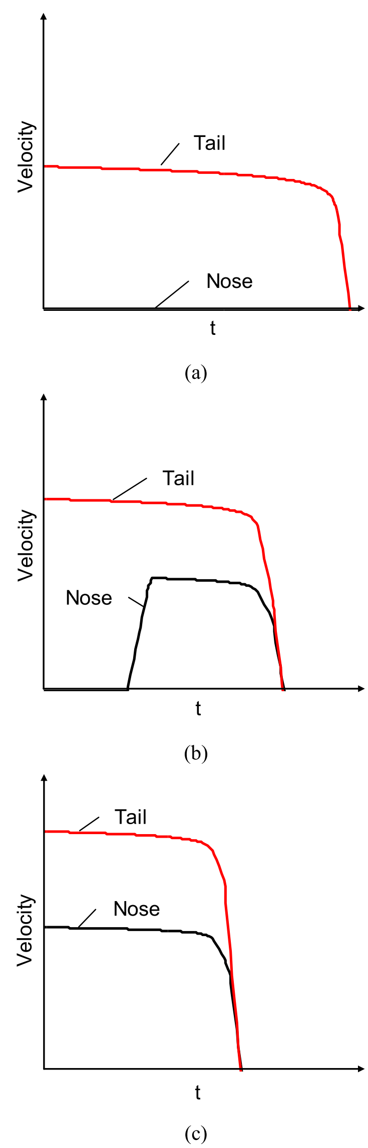

Fig. 2. Nose and tail velocities of long rod versus time under different impact velocities: (a) $v_0 \le v_0^{lower}$, (b) $v_0^{lower} < v_0 < v_0^{upper}$, (c).$v_0 \ge v_0^{upper}$.