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Dwell and penetration of tungsten heavy alloy long-rod penetrators impacting unconfined finite-thickness silicon carbide ceramic targets

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ABSTRACT

Impact experiments with a tungsten heavy alloy long rod projectile against silicon carbide tiles were performed to study the transition from dwell to penetration and to compare against earlier investigations which focused either on small scale semi-infinite set-ups or on finite thickness set-ups with confinement. A depth-of-penetration configuration consisting of a ceramic tile and an extended steel backing was used to assess the impact response of the unconfined finite-thickness ceramic. The ceramic tile was either bare or had a cover plate attached to the front. The cover plate thickness has been varied and gives best results for a thickness of about half the projectile diameter used in the experiments. For the bare ceramic, a long dwell phase can be maintained up to impact velocities of around 900 m/s. For the buffered ceramic, partial dwell can be achieved up to around 1700 m/s. The results corroborate those of earlier investigations mentioned above. More importantly, the present results show that it is possible to substantially erode a heavy alloy long-rod penetrator at the surface of a finite thickness ceramic element without lateral confinement in direct impact experiments even at high impact velocities.

1. Introduction

For the regime of long-rod penetrators impacting at velocities of about 1000 to 2000 m/s onto high-strength targets, the interaction behavior is strongly determined by material properties like strength and hardness [1]. This means that contrary to the fully hydrodynamic regime, weight saving in protective structures is still possible by the application of low density materials as long as their compressive strength is sufficiently high. Therefore, it is a promising approach to use ceramic materials, although their brittleness gives rise to a complex behavior that requires appropriate design of protective elements.

Ceramics also exhibit a mechanism of defeating a projectile known as dwell effect or interface defeat: a high-velocity projectile erodes at the ceramic surface and flows out radially with no significant penetration (Fig. 1). Dependent on material and target set-up, the duration of the dwell effect can vary from a fraction of the projectile interaction time up to a complete erosion of the projectile at the target surface. For the latter case, the term "interface defeat" is frequently used.

The dwell effect for rod penetrators has been investigated in complicated target arrangements about 15–25 years ago, e.g. Refs. 2–4, although the first observation of the basic effect in light armor studies dates back much earlier, e.g. Ref. 5. As reviewed in Ref. 4, many different target layerings with light and heavy confinements were analyzed using direct-impact tests and also small-scale reverse impact tests. Nonetheless, due to the complexity inherent to the target design the key interaction mechanisms were still masked by the overall ballistic response of the setup. Therefore, a natural step was to consider bare and semi-infinite ceramics, in order to focus

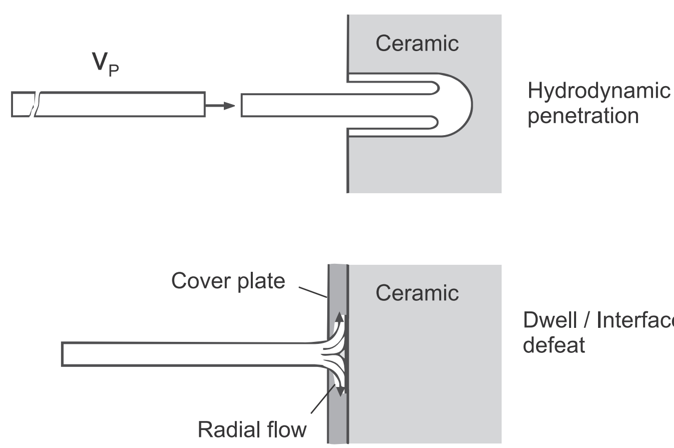

Fig. 1. Principle of the dwell effect. Instead of penetrating into the target, the penetrator erodes at the target surface and flows out radially. The cover plate is optional and determines the transition velocity from dwell to penetration.

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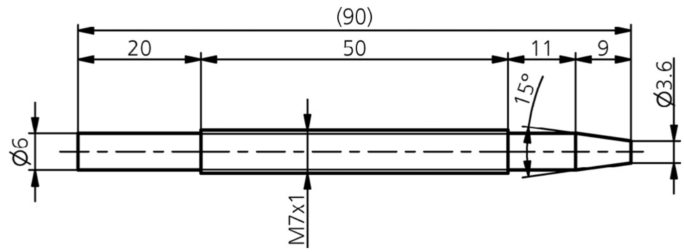

Fig. 2. Penetrator dimensions.

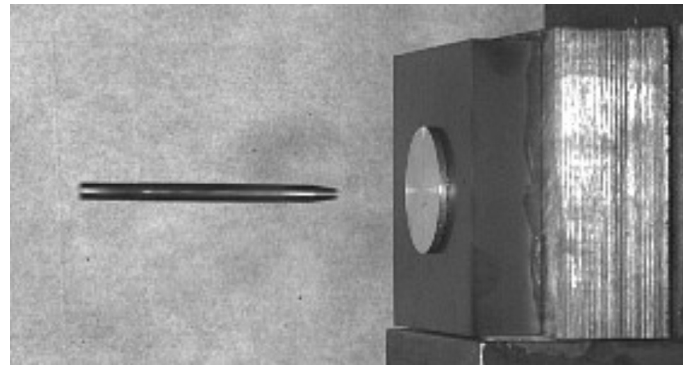

Fig. 3. Frame from high-speed video, showing the experimental set-up inside the impact tank prior to the projectile impact.

on the behavior of the ceramic material. This more academic approach also used small-scale reverse impact experiments and allowed for fundamental characterization of the ceramic material upon high-velocity impact of a long rod [6–13]. Lately, some in-depth theoretical analyses based partly on those small-scale results were also published [14,15].

In the present paper, we address the transferability of the results of the above work to direct impacts of tungsten heavy alloy (WHA) rod penetrators onto single ceramic tiles of limited thickness, only supported by a backing. This implies a significant increase in scale by a factor of 6 for key geometries like rod diameter compared to experiments done in, e.g., Refs. 12 and 13, and at the same time a reduction of the thickness of the ceramics to less than 5 times the projectile diameter, i.e. we aim at extending prior work, e.g. Refs. [12] and [13], to completely different parameter ranges and at corroborating the transferability of well-known basic effects to different dimensions by experimental evidence.

1.1. Experimental set-up

The W-Ni-Fe based generic tungsten-heavy-alloy (WHA) penetrator used in the experiments has a diameter D of 6 mm and a length L of 90 mm. The 9 mm long nose section is conical with a 3.6 mm blunt tip (see Fig. 2). The penetrator material is Kennametal E-922Y. The ceramic targets are quadratic tiles of dimensions 100 mm × 100 mm, 25 mm thick, made of commercial grade, pressureless sintered silicon carbide (SiC). The specific material is designated as SiC-F and is manufactured by 3M (formerly EKasic-F from ESK). A target consists of one SiC tile glued to a rolled homogenous armor (RHA) steel plate of 40 mm thickness. Depending on the impact velocity, additional RHA plates are placed behind the target, in order to ensure a semi-infinite RHA target for penetration measurement. Table 1 shows the key mechanical properties for the different materials.

The sabot-guided projectile was accelerated with a powder gun into a stationary observation tank. The impact was monitored with a multiple anode X-ray tube and a high-speed video camera. The impact velocity was varied between 400 and 1800 m/s. Experiments were carried out for the bare ceramic and for a buffered version, where a small copper disc was glued to the ceramic surface (see Fig. 3). The purpose of the copper buffer is to attenuate the impact shock and to increase the dwell-to-penetration transition velocity compared to a bare surface. The basic effect of such buffers is well-known as, e.g., discussed in Refs. 2, 8, 16, and 17. The buffer thickness was optimized at a constant impact velocity followed by a variation of the velocity for the optimal buffer thickness. Contrary to prior work [17], the buffer thickness identified as reasonable in the present work is smaller than the projectile diameter. Also, unlike in Ref. 16, the buffer is not combined with lateral confinement.

2. Experimental results

Table 2 shows the results for the bare ceramic targets (9 experiments). Total yaw angle, impact velocity v_P and residual penetration depth P_R into the supporting RHA plates were measured. The area density of the penetrated material for the complete target arrangement calculates as

$$\rho_A = \rho_{SiC} \cdot l_{SiC} + \rho_{RHA} \cdot P_R \tag{1}$$

from the densities ρ_{SiC} and ρ_{RHA} of ceramic and backing, respectively, the thickness of the ceramic l_{SiC} and the residual penetration in the backing P_R. The standard velocity measurement procedure yields an error of about 1 %. The error for the depth measurement is about ± 0.1 mm.

Results for the buffered target configurations are given in Table 3 (8 experiments). In addition to the data of Table 2 the buffer thicknesses l_{Cu} is incorporated. Accordingly, the area density of the penetrated material for the buffered target arrangement calculates with the density ρ_{Cu} of the buffer as:

$$\rho_A = \rho_{Cu} \cdot l_{Cu} + \rho_{SiC} \cdot l_{SiC} + \rho_{RHA} \cdot P_R \tag{2}$$

Table 1
Key mechanical properties.

Material	WHA	SiC	RHA	Cu
Source	Certificate	Datasheet	Specification	Datasheet
Density [g/cm^3]	17.6	>3.15	7.85	8.9
Ultimate tensile strength [N/mm^2]	1360	–	900	~270
Elongation at fracture [%]	10	–	12	~20
Hardness	475 HV 10	2650 HV 0.5	280–330 HBW	~80 HB
Elastic modulus [GPa]	–	430	–	–
Flexural strength [GPa]	–	400	–	–
Compressive strength [GPa]	–	>2500	–	–
Fracture toughness [MPa m$^{0.5}$]	–	4	–	–