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OBLIQUE PENETRATION IN CERAMIC TARGETS

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Metallic targets have higher mass efficiencies when the target is placed at oblique angles to the penetrator flight path. The objective of this study was to determine if obliquity increased the mass efficiency of ceramic-faced targets. An experimental and computational investigation was conducted to study the effect of obliquity for alumina-faced targets. In a series of experiments, 7.62-mm AP projectiles were fired at alumina tiles backed by aluminum substrates oriented at 0, 45 and 60 degrees. The targets had the same *areal densities (AD)* in the *line of fire (LOF)*. The residual DOPs were measured in aluminum blocks mounted behind the targets. The experiments were simulated using the AUTODYN-3D Lagrangian hydrocode. The results showed that ceramic targets perform better at normal incidence than at obliquity for the same *AD* at the *LOF*.

INTRODUCTION

It is very well known that the ballistic *mass efficiency of metallic* targets against kinetic energy penetrators is strongly dependent upon the impact obliquity. Asymmetric forces acting on the projectile during the entry and exit phases are responsible for this effect. In general, the higher the obliquity, the better the mass efficiency. This is one of the reasons armored vehicles are designed with glacis and slopped walls at the front, and sometimes at the sides, of the vehicles. This effect in metal targets has been demonstrated experimentally and theoretically in many studies (see, for example [1–3]).

For metallic targets, there is an increase in performance of the target over and above the increase in the line-of-fire (LOF) thickness. The LOF thickness is given by the simple geometric relation:

$$t_{LOF} = \frac{t}{\cos\theta}$$

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where t_{LOF} is the line-of-fire thickness, t is the normal thickness, and θ is the obliquity angle. The ballistic limit thicknesses, at 0° and 45° obliquity, for various targets against the 7.62-mm APM2 bullet, shot at muzzle velocity, are shown in Fig. 1. The LOF thickness for the 45° targets was calculated, and it is also displayed in the figure. For the targets in which there exist data for both 0° and 45° obliquity, it is seen that less LOF target thickness is required to defeat the bullet. That is, obliquity results in further weight savings tban would be calculated using the simple geometric factor of the inverse cosine. In fact, to a first approximation, the increase in effectiveness is approximately given by the product of the projectile diameter (D) and tan θ. Thus, one might expect even more weight savings at higher obliquities.

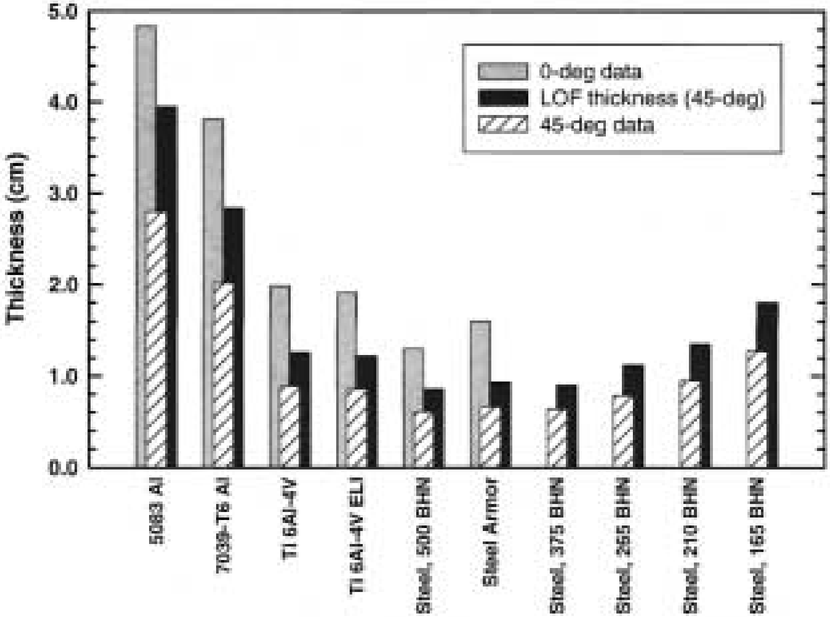

Figure 1. The ballistic limit thicknesses of metallic targets to the 7.62-mm APM2 projectile for muzzle velocity at 0° and 45° obliquity.

The effect of obliquity on the ballistic performance of composite armor against ball projectiles was studied in [4], where it was found that mass efficiency increased with obliquity. This effect is ambiguous in *fabric* armor; fabrics exhibit higher ballistic efficiency only at a limited range of obliquities [5]. It was shown in Ref. [6] that the mass efficiency of alumina/aluminum targets against 14.5-mm AP projectiles decreases strongly with obliquity.

In this study, we investigate the effects of obliquity for alumina/aluminum targets against a smaller caliber bullet – the 7.62-mm APM2 – and suggest a physical explanation for the observed phenomenon by means of experiments and numerical simulations. The ceramic-faced targets have the same component thicknesses and the same *areal densities (AD)* in the *line of fire (LOF)*, as shown in Fig. 2.

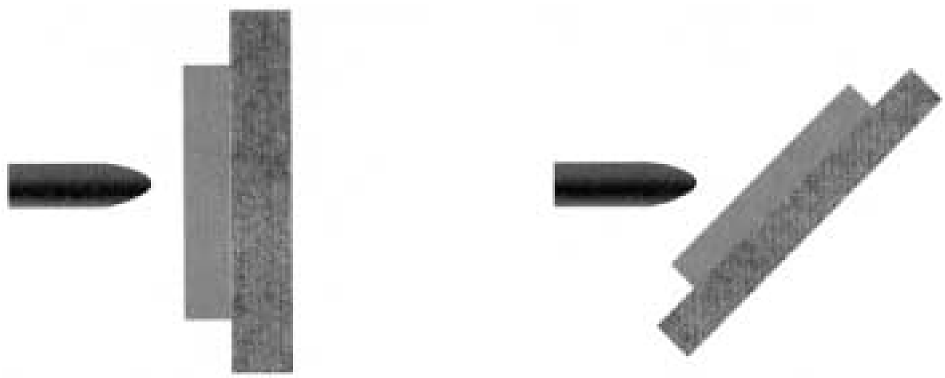

Figure 2. Schematic of experimental arrangement, line-of-fire thickness held constant.

EXPERIMENTS

In a series of experiments, 7.62-mm APM2 projectiles were fired on Al_2O_3 tiles backed by aluminum substrates at muzzIe velocity (840–850 m/s). The targets consisted of an Al_2O_3 tile, 3.1 to 9.2-mm thick, backed by an aluminum (6061-T6) substrate, 3.1 to 6.6-mm thick. Experiments were conducted at impact obliquities of 0, 45 and 60 degrees (NATO). The targets were constructed in sets so that for every oblique target, there also was a zero-degree target with the same *AD* in the *LOF* direction. The experimental procedure is shown in Fig. 3.

The $A1_2O_3$ tiles were approximately 50 mm by 50 mm; the tiles were glued to aluminum substrates that were 200 mm by 200 mm. The$A1_2O_3$ tiles were AL98 from *Rami Ceramics*, Israel; mechanical properties of the AL98 are given in Table 1.

Table 1: Al_20_3 (AI98) properties

Density	3.80 g/cm^3
Bend Strength	320 MPa
Hardness	1389 kg/mm^2
Sound velocity	10.2 km/s

The *depth-of-penetration (DOP)* technique, first introduced in [6–7], was used to evaluate the ballistic performance of the targets. The residual DOP values were measured in an A1 6061-T6 block mounted 50 mm behind the ceramic-faced targets. From the experimental results, the *mass efficiencies* (E_m) of the targets were calculated from Eq. (2). In Eq. (2), the numerator is the areal density of “semi-infinite” 6061-T6 aluminum penetrated by the APM2 bullet (which is a function of the impact velocity *V)*. The denominator is the sum of the areal densities of the target components (along the *LOF*) plus the areal density penetrated (measured by the *DOP*) into the aluminum witness block. The baseline penetration into aluminum versus impact velocity curve was experimentally determined in order to eliminate variations in impact velocity (around the muzzle velocity) [8].

$$E_m = \frac{(\rho_{Al} DOP_{Al}[V])_{\infty}}{(\rho t)_{Al2O3} + (\rho t)_{Al} + \rho_{Al} DOP_{exp}}$$

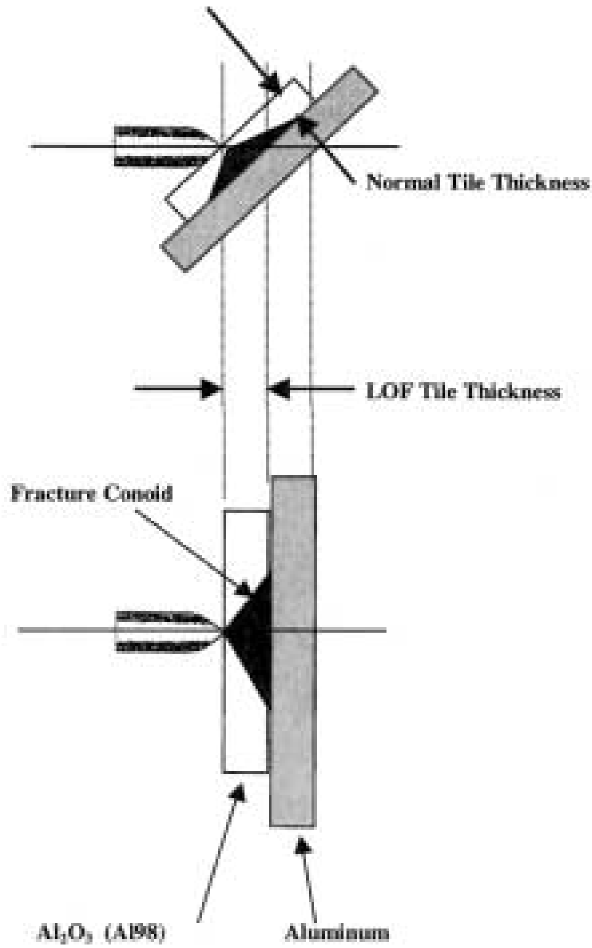

Figure 3. The experimental procedure.

EXPERIMENTAL RESULTS

The impact conditions and results of the experiments are summarized in Table 2. The results are also shown graphically in Fig. 4. The targets are arranged in increasing areal density along the abscissa, and where multiple targets were tested, the spread in E_m is also shown. The results indicate that ceramic/aluminum targets perform better at normal incident than at obliquity for the same *AD* at *LOF*. The trend for E_m to decrease with increasing tile thickness ist also observed in the data.

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Table 2. Experimental data and results

Test #	Obliquity [NATO]	Al_2O_3 Thick [mm]	Al Thick [mm]	*V* [m/s]	*AD* in *LOF* [g/cm^2]	*DOP* [mm]		E_m
						Results	Average	
16	0°	6.6	4.8	854	3.8	4.8	4.4	2.8
17				860		5.1		
18				845		3.3		
13	45°	4.6	3.1	853	3.7	7.1	8.4	2.4
14				860		11.0		
15				849		7.1		
22	0°	9.2[1]	6.6	841	5.3	2.0	1.9	2.4
23				855		2.2		
24				845		1.5		
19	60°	4.6	3.1	838	5.2	4.6	5.4	2.0
20				840		4.6		
21				845		6.9		
689	0°	8.0[2]	6.6	835	4.9	0	0	2.7
688	60°	4.2	3.1	827	4.9	6.4	6.4	2.0
690	0°	6.5	6.6	833	4.2	2.9	2.9	2.7
687	60°	3.1	3.1	839	4.0	6.2	6.2	2.4

[1] Two 4.6-mm tiles glued together
[2] AD995 alumina

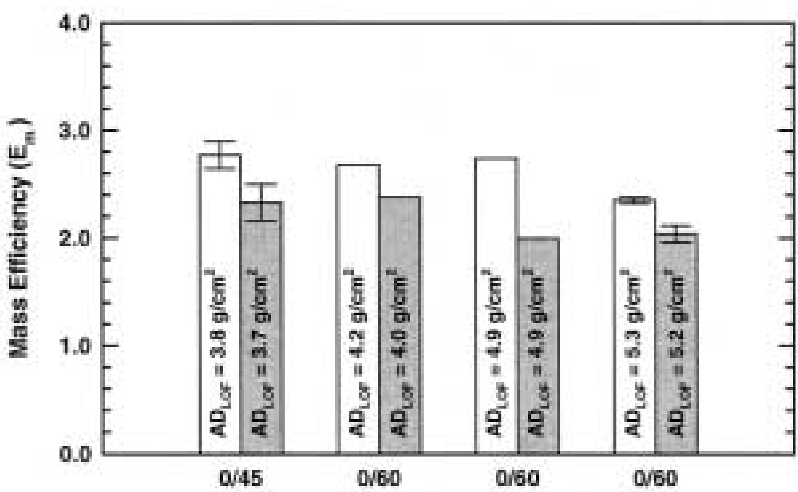

Figure 4. Experimental results.

3-D NUMERICAL SIMULATIONS

Four of the tests presented in Table 2 were simulated with the commercial hydrocode AUTODYN-3D [9]. The total number of nodes used in the Lagrangian mesh was approximately 50,000. The bullet was modeled as a hard steel core, with lead in the front, all surrounded by the gilding jacket. Stress-strain measurements of the hard steel core [10] permitted an estimate for the constants in the Johnson-Cook constitutive model [11]. The gilding material model as well as that for the lead came from the library of the numerical program. The Johnson-Holmquist brittle material model was used to model the ceramic [12].

Each simulation consisted of two different parts. First, the simulation of the normal or oblique impact was performed, from which the residual velocity and length of the projectile were obtained. The second step was to simulate the impact of this residual projectile into a semi-infinite block of aluminum to obtain a computational *DOP*. The penetration/perforation of the ceramic/aluminum target and the *DOP* calculation were done separately to optimize the use of computational nodes and CPU time.

The objective of the computational study was to evaluate qualitatively the influence of obliquity on ceramic failure. However, to have some confidence in the computational results, it was necessary to reproduce reasonably accurately the measured *DOP's* into the aluminum witness block. The normal impacts were used as a reference for the oblique impacts. Fig. 5 shows the initial configuration for normal impact into the ceramic-faced target.

Table 3. Experimental and numerical comparisons

Test number	DOP test (mm)	DOP numerical
16	4.4	6
13	8.4	9
689	0	2
688	6.4	4

The results for the numerical simulations are shown in Table 3. Agreement is reasonable, although not perfect, for the normal impact simulations (numbers 16 and 689). The simulation results for test numbers 13 and 688, which are for 45 and 60 degrees obliquity, respectively, show the appropriate trend, i.e., a decrease in DOP into the witness block.

Figure 6 is a close-up view of the bullet and material status 12 μs after impact. The gilding and the lead are being eroded. Even though the core is just coming into contact with the ceramic, the ceramic is already damaged in the front and at the ceramic/aluminum interface. In fact, the simulations indicate that the gilding metal jacket and lead initiate damage in the ceramic, diminishing the ceramic resistance to penetration by the core. The image also shows, as suspected, that the damage propagates perpendicular to the ceramic surface. Since the ceramic is thinner than for the normal impact case, overall through-thickness failure occurs earlier for the oblique target. This observation was confirmed in both the 45 and 60 degrees obliquity impacts.

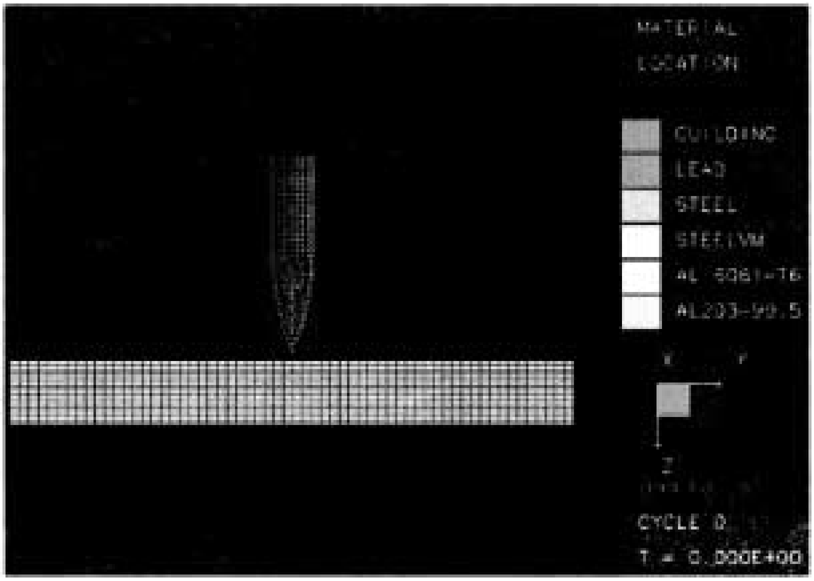

Figure 5. Initial configuration showing the mesh and materials.

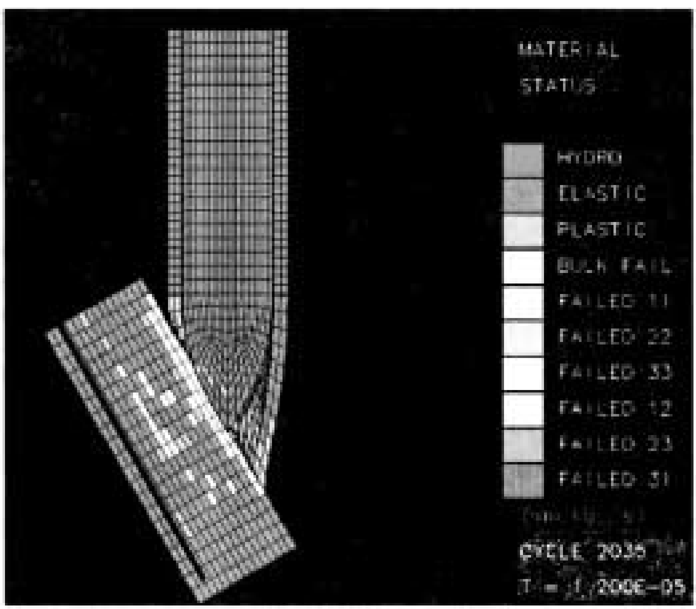

Figure 6. Material status 12 μs after oblique, 60 degrees, impact.

CONCLUSIONS

Ceramic targets perform better at normal incident that at obliquity for the same areal density in the line of fire. It was speculated that this effect was due to the sequence of damage in the ceramic element, which was confirmed by numerical simulations. The projectile moves along the *LOF*, but the timing of the damage in the ceramic tile depends on the tile thickness in the *normal direction*. Therefore, thinner tiles fracture earlier (see Figs. 3 and 6). The substrate is also thinner for the oblique configurations. Ceramic performance is a function of substrate stiffness. Therefore, substrate stiffness is less for the oblique target than for the normal configuration. However, the primary reason for the poorer ballistic performance of ceramic-faced targets at oblique angles, compared to an equal *LOF* areal density for normal target obliquity, is due to the mechanics of damage propagation within the ceramic tile.

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