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PENETRATION OF AP PROJECTILES INTO SPACED CERAMIC TARGETS

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Experimental and computational work was conducted to study the effect of ceramic spaced targets on the performance of AP projectiles. The base-line target is a single element system consisting of alumna/aluminum laminates. The ballistic performance of this target is compared with the performance of a spaced system having an equivalent arial density. The experimental results are discussed and compared with results of simulations. For the experimental evaluation of target performance we used the Depth-of-penetration (DOP) technique. For the computational investigation we represented the failed ceramic by the Mohr-Coulomb model and used the Euler processor of the 2D AUTODYN hydrocode.

INTRODUCTION

Ceramic faced configurations are increasingly considered for armor applications where weight efficiency is the major constraint. Wilkins presented experimental data to determine the best ratio of ceramic tile to back-up substrate thickness, against armor piercing (AP) projectiles [1,2]. The performance of ceramic faced armor can be enhanced by optimizing the laminated ceramic-tile/substrate configurations [3–6].

The purpose of the present study is to investigate the influence of spaced ceramic configurations on their ability to defeat small AP projectiles. The ballistic performance of the spaced system is compared with the performance of a single (non-spaced) ceramic element having an equivalent arial density.

The rationale for this study is based on the observation that the maximum resistance of a ceramic material to penetration occurs at the early phase of the penetration process. At this stage, much of the ceramic tile is still intact, before it undergoes fracture. This phenomenon has been observed both for thin ceramic faced targets against small AP projectiles [1], and for thick ceramic targets against long rod penetrators [7–9]. It may be explained by the projectile dwell at the surface of the ceramic [10]. It is not clear whether a spaced system has a longer total dwell phase compared to an equivalent single element system.

EXPERIMENTS

In a series of experiments, 7.62 mm AP M2 projectiles were fired at alumina tiles backed by aluminum substrates at, or around, the standard muzzle velocity (840–850 m/s). The single element system consists of a 9.2 mm thick Al_2O_3 tile, backed by a 6.6 mm thick aluminum substrate. The spaced system consists of two 4.6 mm thick Al_2O_3 tiles, each backed by a 3.1 mm thick aluminum substrate. The two elements are separated by a 82 mm space (three core lengths). See Fig. 1.

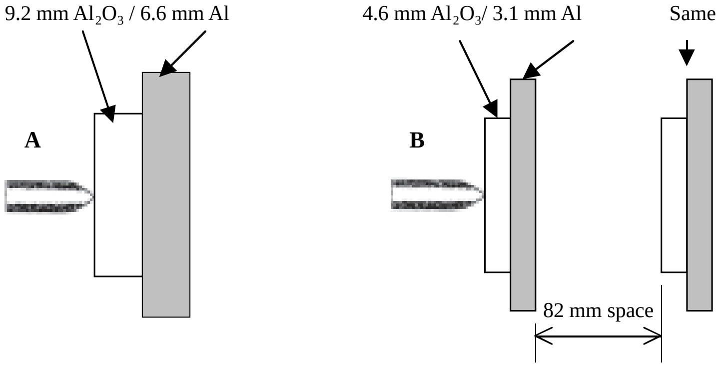

FIGURE 1: Test Configurations: A = Single Element target, B = spaced target.

All Al_2O_3 tiles are 2" x 2" wide, and all aluminum substrates are 8" x 8" wide. The Al_2O_3 tiles are Al98 from Rami Ceramics, Israel. Their properties are: Density = 3.80 g/cm^3, Bending Strength = 320 Mpa, Hardness = 1389 kg/mm^2, Sound Speed = 10,200 m/s. The aluminum plates are Al6061-T6.

In order to evaluate the ballistic performance of the targets we applied the depth-of-penetration (DOP) technique, which was first introduced in [3,4]. The residual DOP values were measured in an aluminum Al 6061-T6 block mounted 2" behind the target. From the results, the *mass efficiency* (Em) of the targets is calculated. Em is defined as *the arial density of the total penetrated part of the target, relative to the arial density of the base line penetration in an all aluminum target.* The base line penetration versus impact velocity curve was experimentally determined in order to eliminate variations in impact velocity (around the muzzle velocity).

Digital Imaging 468 Imacon camera recorded the impact and penetration events, but the ceramic debris behind the targets covered the residual cores. Therefore, in two tests the residual cores were recovered in a soft catcher mounted behind the target (instead of DOP blocks).

TEST RESULTS

The tests and their results are given in Table 1.

Table 1. Experimental data and results

Test No.	Configuration	Velocity [m/s]	Arial Density [kg/cm^2]	DOP [mm]	Average DOP [mm]	E_m	Recovered Core
22	A	841	5.27	2.0	1.9	2.4	-
23		855		2.2			-
24		845		1.5			-
586	B	838	5.17	4.5	4.8	2.1	-
662		833		5.0			-
691	B	842	5.17	-	-	-	Eroded and broken
192	One element of B	835	2.58	-	-	-	Tip eroded

From the test results the following conclusions may be drawn:

– The ballistic performance of a single element system (configuration A) is higher than that of a spaced system having the same arial density (configuration B).
– Two elements of the Al_2O_3 spaced system break the core but one element of the spaced system does not break the core.

SIMULATIONS

Before running simulations for the targets used in the tests, it is desirable to calibrate the simulations for a simple aluminum plate target. For this purpose we use data obtained by one of us (D. Yaziv) with a blunt (backward moving) AP M2 projectile perforating a 6.6 mm 6061-T6 aluminum plate. For our simulations we use the Euler processor of AUTODYN2D version 4. In Fig. 2 we sum up the results from these simulations, and compare them with the test data. We see that, in view of the scatter and uncertainties in both tests and simulations, agreement is good. In subsequent simulations we use Y=0.4 GPa for 6061-T6 aluminum, as this value gave the best agreement.

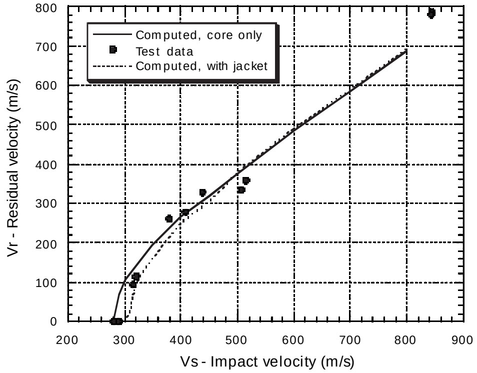

Figure 2. $V_S V_r$ plot of a blunt AP projectile perforating a 6.6 mm 6061-T6 aluminum target.

Next we conduct an extensive computational investigation on the performance of a spaced target compared to a non-spaced target of the same thickness. As before, we use AUTODYN2D/Euler. We report results relating to the following cases:

- Depth of penetration (DOP) of blunt and pointed projectile cores into 6061-T6 aluminum witness plates.
- Performance of spaced aluminum targets against flat projectile cores.
- Performance of spaced ceramic/substrate targets against blunt projectile cores, compared to non-spaced targets of the same thickness.

DOP Tests of Blunt and Pointed Projectile Cores into Aluminum Targets

The reason for addressing this case before running the main simulations is to check whether, what we obtain agrees with test data that we have. We ran simulations for a pointed high hardness steel projectile representing the AP M2 core. According to our experience, running simulations for the core would represent quite well the performance of a jacketed projectile. Running for V_S=600 m/s we obtained DOP = 16.5 mm, which is much lower than the data (28 mm). We tried lower values of strength for the aluminum and got the results summarized in Table 2.

Table 2. DOP for different aluminum strength values.

Y GPa	DOP mm
0.4	16.5
0.3	19.5
0.2	25.5

We see that to get realistic DOP values into witness blocks, we need to use Y≈0.2 GPa for thin 6061-T6 aluminum plates.

In Fig. 3 we show DOP results from runs with blunt and pointed projectiles into aluminum blocks with Y=0.2Gpa.

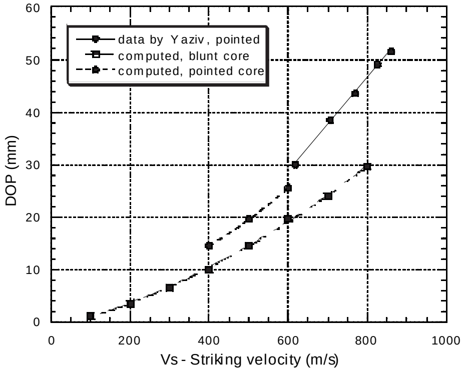

Figure 3. DOP for blunt and pointed projectiles, representing the AP M2 projectile core, into 6061-T6 aluminum, with Y=0.2GPa.

Performance of Spaced Aluminum Targets against Blunt Projectile Cores

Having generated DOP(V) curves, we proceed to compute V_sV_r curves for spaced aluminum targets. Using our DOP(V) curves we can express the residual velocity V_r in terms of DOP into a witness block. Our goal is to evaluate computationally the performance of spaced ceramic/substrate targets. But for comparison, we evaluate also the performance of spaced aluminum targets. This will help us later to eliminate possible explanations of the behavior of the ceramic targets.

In Fig. 4 we show the results of our computations in a V_sV_r plot. We see three curves: blunt projectile perforating a 6.6 mm aluminum plate; same, but with a 3.3 mm plate; same projectile, but with two spaced 3.3 mm plates.

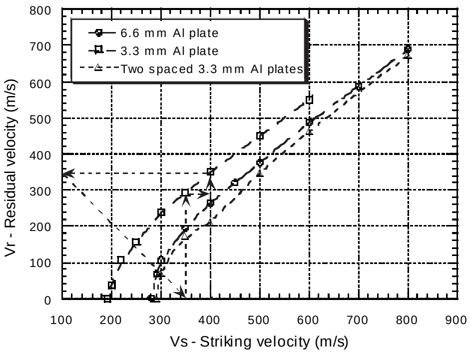

Figure 4. V_sV_r Plot for blunt projectile cores against 3.3, 6.6 and spaced 2x3.3 mm aluminum plates.

We see that the three curves have similar shapes, and that the performance of the spaced target (2x3.3 mm) is somewhat lower than that of the 6.6 mm target. Above $V_s=300$ m/s, the difference in V_r is about 40 m/s.

One can try to deduce the performance of the spaced target from that of the 3.3 mm target, assuming that V_r behind the first plate is V_s for the second plate. Doing this for $V_s=400$ m/s we get $V_r=290$ m/s. This is higher than V_r for a 6.6 mm plate (265 m/s), in disagreement with the direct simulations. The cause for this discrepancy is that in the simulations, the projectile pushes a plug out of the first plate. This plug is somewhat wider than the projectile and is less effective than the bare projectile in perforating the second plate. This plug effect should be considered when transforming a residual velocity to DOP into a witness block.

Performance of Spaced Ceramic/Substrate Targets against Blunt Projectile Cores

The ceramic in the tests is 3.80 gr/cc alumina. We represent the strength of failed ceramic by a Mohr-Coulomb model. We assume that during the penetration process the ceramic has already failed, and ignore the transition phase from intact to failed states. After some trials we chose to use the following Mohr-Coulomb relation: $Y=0$ for $P\le0$; $Y=P$ for $0<P\le1$GPa; $Y=1$GPa for $P>1$GPa.

In Fig. 5 we show V_sV_r results for the blunt projectile core perforating the following three targets: thick ceramic/substrate (9.2/6.6 mm), thin ceramic/substrate (4.6/3.3 mm), and two spaced thin ceramic/substrate targets (2 x 4.6/3.3 mm). We see from Fig. 5 that the spaced target has a significant disadvantage compared with the non-spaced target of the same thickness. This is in agreement with the tests.

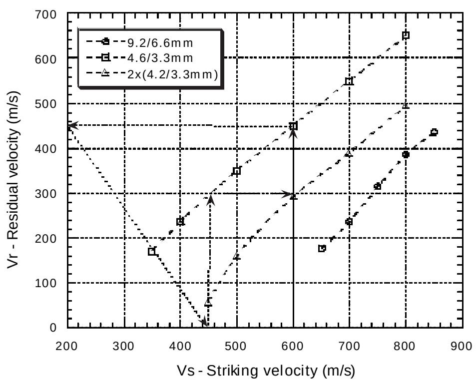

Figure 5. Computed results for a blunt projectile perforating ceramic/substrate targets.

We should emphasize that the spaced target effect occurs in the simulations without any recourse to sophisticated damage models. Assuming the ceramic to be damaged, the effect is purely hydrodynamic. In Fig. 5 we also show, as in Fig. 4, prediction of the spaced target performance using the V_sV_r plot for the thin target. Comparing Figs. 4 and 5, it seems that the spaced target effect depends on the overall thickness of the target. V_sV_r plots of a thick target and of a target half that thickness would be far apart, and we would get a large spaced target effect. To show that, we conducted runs with blunt projectiles perforating thicker aluminum plates as follows: A 6.6 mm plate (from Fig. 3), a 13.2 mm plate, and two spaced 6.6 mm plates. We show the results in Fig. 6. We see that this time the spaced target curve is above the non-spaced thick (13.2 mm) target curve, although not by much.

SUMMARY

We conducted AUTODYN2D/Euler computer simulations to investigate the spaced target effect observed in our tests namely, that a spaced ceramic/substrate target (2 x (4.6/3.3 mm)) has a significant disadvantage to perforation by a blunt projectile core, compared with a non-spaced (9.2/6.6 mm) target. After some calibration runs we performed 4 sets of computations, summarized in Figs. 3 to 6.

Our conclusions are:

– The spaced target effect is a hydrodynamic effect and may occur for all kinds of targets.

– The space target effect may be observed for relatively thick targets, when the V_sV_r curves for thick and half thickness targets are significantly apart.
– For aluminum plates a plug effect, that tends to offset the spaced target effect, occurs in the simulations.
– The plug effect for ceramic/substrate targets is quite small so that the spaced target effect for them is more pronounced.

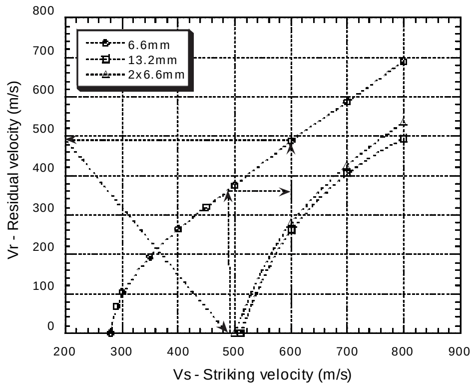

Figure 6. Computed results for a blunt projectile perforating 6.6,13.2 and 2x6.6 mm aluminum targets.

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