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COMPARATIVE ANALYSIS OF OBLIQUE IMPACT ON CERAMIC COMPOSITE SYSTEMS

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Abstract — An experimental programme is presented which investigated the performance of oblique, ceramic/metal, bilayer composite armours. The ceramics, alumina and silicon carbide, were backed by either Rolled Homogeneous Armour steel (RHA) or 7000 series aluminium. Using a model scale tungsten penetrator at two velocities (representing current and future ordnance threats) the effect of configuration on ballistic limit or depth of penetration (DOP) areal densities was determined. Areal densities of the DOP targets decreased with increasing ceramic thickness, achieving a minimum at zero residual penetration in the backing. The bilayer targets, loaded at the ballistic limit needed a larger areal density to defeat the penetrator. This areal density also decreased with ceramic thickness but showed a minimum with respect to ceramic thickness, as a result of reduced support by the thinner metallic backing. At 1450ms^{-1} the most efficient system was found to be a SiC/Al, which demonstrated a 25% weight saving over the monolithic aluminium reference target. The Al-alloy backing performs better than RHA, and SiC better than Al_2O_3. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Ceramic, alumina, silicon carbide, ballistic limit, depth of penetration, oblique impact, mass efficiency factor, bilayer target, composite armour.

NOTATION

BL	ballistic limit
DOP	depth of penetration
Al	aluminium alloy
RHA	rolled homogeneous armour steel (UK)
AO	alumina Al_2O_3
SiC	silicon carbide SiC
$\rho_{A,\,tot}$	total penetrated areal density
$\Delta\rho_{A,\,tot}$	Increase in areal density required between BL and DOP configurations
MEF_{Al}	mass efficiency factor of target with respect to Al
MEF_{RHA}	mass efficiency factor of target with respect to RHA
v_p	impact velocity
$\Delta\, v_p$	velocity range of a test series
LOS	line of sight
$\rho_{A,\,Cer}$	areal density of the ceramic sheet

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INTRODUCTION

The method for determining the protective capability of a hard ceramic front layer, by measuring the residual Depth of Penetration into a ductile metallic backing (the DOP method) has been used successfully by many authors [1-13]. On the other hand only a few authors have used the ballistic limit method to determine the combination of a hard ceramic front and a ductile backing sufficiently thick to only just defeat a given projectile [14-16]. Both methods give a good ranking capability for the determination of a 'goodness' coefficient (Mass Efficiency Factor and others) for different materials, but the different methods tend to favour different characteristics of both the hard face and ductile backing [16].

Most ranking experiments reported in the literature have been for normal impact. Very little comparative data exists for oblique impact on ceramic materials [16-18]. This is due in part to the difficulties in the numerical simulation of oblique impact experiments, for which fully 3-dimensional simulations must be run.

The experiments reported here constitute part of our effort to determine the effects that change the performance of ceramic materials when the backing is changed from a structure with maximum stiffness (semi-infinite backing) to a structure which is free to bend and stretch (ballistic limit configuration). The DOP-tests were performed for normal impact. The ballistic limit experiments were performed such that the projectile impacted at an angle of 60° to the normal to the surface of the target, to be more readily compatible with the requirements of real armour systems. The ceramics Al_2O_3 and SiC were backed by RHA and an Al-alloy.

The experiments were performed at an approximate half scale, predominantly at $1450 ms^{-1}$, to represent the attack of a generic medium calibre cannon long rod projectile on an inclined ceramic armour system. Further tests were conducted at $2200 ms^{-1}$ to study the armour response against future ordnance velocity impacts.

EXPERIMENTAL PROCEDURE

A re-usable target jig was designed to enable cost effective, reliable and repeatable assembly and impact of layered targets at an obliquity of 60° ± 0.2° from the surface normal. A normal impact jig was also built giving equivalent accuracy. A clamping device was built into the jig to give an axial compressive force along the lateral edges of the tiles (6mm overlap each side). No lateral compression was used. All oblique targets were 100mm x 150mm, giving a presented area 88mm wide by 75mm high (allowing for the 6mm clamping plates either side).

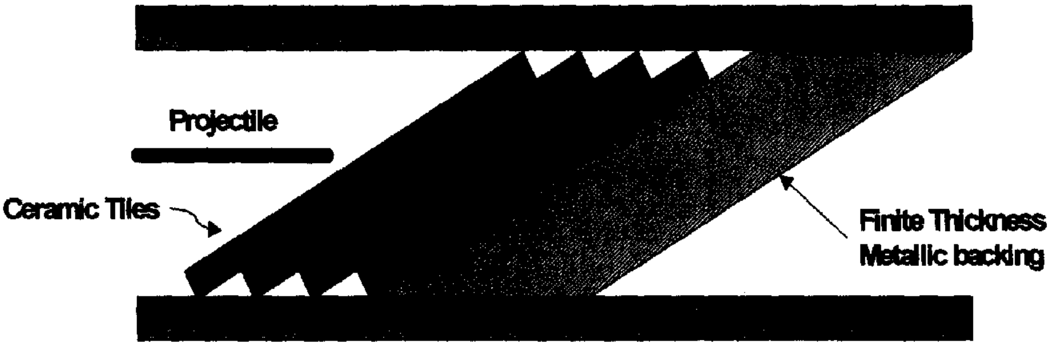

Fig. 1. Diagram of stacking in angled target jig

All mating surfaces of the ceramic tiles and the metal backing plates were machined to a flatness of ± 5.0μm and a surface finish of 0.4μm CLA. No adhesive was used in any of the arrays. Whilst some benefit may accrue from the use of an adhesive [19, 20], it was felt that the repeatability would be greater with carefully machined surfaces only. DOP tests were performed with a selected ceramic sheet thickness. Metal backing plates were machined to thickness with a wedge angle on the upper and lower lateral edges, to fill the space within the target jig (see Figure 1). The 8.7mm high gaps at the edges of the ceramic tiles were not filled. A photograph and cutaway drawing of the target assembly may be seen in Figure 2.

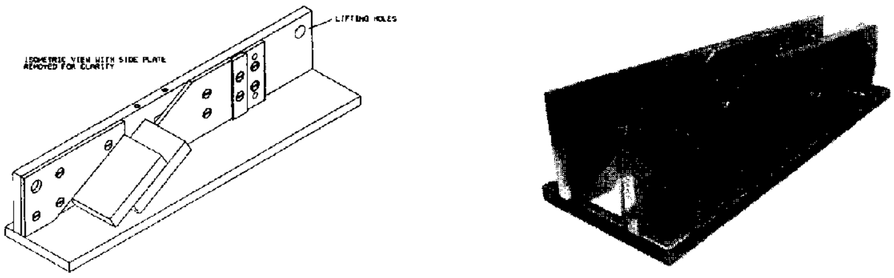

Fig. 2. Cutaway diagram and photograph of target assembly

The projectile (71mm long L/D=20, see Figure 3) was made from Plansee FNC tungsten sintered alloy. Two systems were used to launch the projectile; a 25mm smooth bore gun using a two part aluminium alloy sabot and a nylon stabilisation flare at 1450ms^{-1}; and a 22mm two stage light gas gun using with a four part sabot and polycarbonate pusher (which could achieve the higher velocity of 2200 ms^{-1}). Impact yaw and yawing rate were measured by high speed photography or flash X-ray before impact and observed to be low. All impacts were close to the centre of the tile.

Table 1. Material properties

Material	Density kg m^{-3}	Young's Modulus GPa	Shear Modulus GPa	Poisson's Ratio	Yield Stress MPa	HEL GPa
Alumina **Morgan Matroc Sintox FA**	3694	308	122	0.24	-	6.5
Silicon Carbide **Cercom SiC PAD-B**	3216	453	195	0.16	-	15.7
Steel **UK RHA**	7838	212	82	0.29	950	-
Aluminium alloy **Al-1318B (7017)**	2780	71	27	0.34	460	-
Tungsten sintered alloy **Plansee FNC**	17600	314	122	0.29	1048	-

Impact experiments were performed with semi-infinite backing blocks to determine the DOP for normal impact incidence and with finite thickness backing blocks to determine the ballistic limit for oblique impact. Ceramic layers were built up from tiles of thickness 10mm. Where necessary, 5 mm tiles were attached at the ceramic sheet front side to attain the required dimension. The metallic backing layer was machined to the thickness required to determine the ballistic limit for a given ceramic layer thickness. Depths of penetration into the semi-infinite backings were determined by sectioning. The undefeated ballistic limit backings were also sectioned to determine the extent of the residual material in order better to estimate the thickness required to obtain the ballistic limit. The areal density required to defeat the round was calculated for both ballistic limit and semi-infinite targets. The uncertainty in the areal density was also estimated.

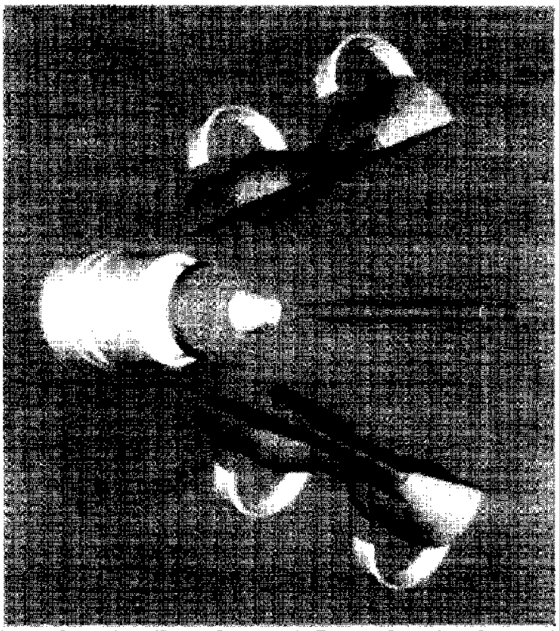

Fig. 3. Drawing of projectile, sabot and flare, showing bore riders and pusher

RESULTS

The results of the DOP tests at 0° target obliquity and of the ballistic limit tests at 60° target obliquity are summarized in Table 2 and Table 3. Figure 4 shows an example of no perforation and perforation of an Al backing plate. Two to six tests were needed to determine the backing thickness at ballistic limit loading. Only tests with yaw angles <1.5° have been accepted.

The impact velocities of most of the tests could not be kept exactly constant at 1450 ms^{-1} or 2200 ms^{-1}. Therefore the penetration in the semi-infinite backing (DOP test) as well as the penetration into the finite thickness backing, including the residual penetration in the witness plate in the case of perforation (ballistic limit test) was corrected with respect to the velocities of interest (1450 ms^{-1} and 2200 ms^{-1}). This velocity correction was done on the basis of the penetration curve in the semi-infinite RHA or Al target. The velocity deviations, Δv_P, occurring during the test series are listed in Table 2 and Table 3.

The total penetrated line of sight areal densities, $\rho_{A\ tot}$, of the laminated targets are plotted in Figure 5. To enable performance ranking of the composite targets, DOP and BL reference tests were performed on the metallic backings. An indication of the uncertainties in the estimated ballistic limit backing thickness are given in Table 2 and Table 3. Except for the case of the AO/RHA BL targets, these uncertainties are not shown in Figure 5 for clarity, since they are the same magnitude as the symbols. Their influence on the trends observed can therefore be considered to be negligible. Table 4 lists the lightest configuration for each target type, and shows the mass saving over the monolithic aluminium reference target in each case.

Figure 6 to Figure 9 show calculated mass efficiency factors, MEF, with respect to the aluminium or RHA backing (MEF_{Al} and MEF_{RHA} respectively), as a function of the LOS ceramic thickness. The two performance variables plotted, $MEF_{CERAMIC}$ and MEF_{SYSTEM}, are defined in Equations 1 and 2 respectively. They evaluate the performance of the ceramic phase alone as well as the system as a whole. The reference target was taken as the semi-infinite Al or RHA target for the DOP tests, and the single oblique Al or RHA plate for the ballistic limit tests.

$$MEF_{SYS} = \frac{\rho_{A,\text{reference metal}}}{\rho_{A,tot}} \tag{1}$$

$$MEF_{CER} = \frac{\rho_{backing}\left(t_{ref} - t_{backing}\right)}{\rho_{ceramic}\left(t_{ceramic}\right)} \quad (2)$$

t_{ref}	Penetrated LOS thickness of reference target
$t_{backing}$	Penetrated LOS thickness of metallic backing used in target system
$t_{ceramic}$	LOS thickness of ceramic
$\rho_{A,reference\ metal}$	Total penetrated areal density in reference target
$\rho_{A,tot}$	Total penetrated areal density of target.
$\rho_{backing}$	Density of backing material, $\rho_{ceramic}$ = density of ceramic

Table 2. DOP and ballistic limit data at 1450 ms^{-1} ($\Delta v_P = \pm$ 50 ms^{-1})

Target LOS [mm]	Test Method	$\rho_{A\ tot\ (LOS)}$ [kg/m^2]	MEF $_{SYS-Al}$	MEF $_{SYS-RHA}$
RHA Baseline				
50 ± 1 RHA	DOP, 0°	390	0.60	1.00
56 ± 2 RHA	BL, 60°	437	0.75	1.00
Aluminium Baseline				
84 ± 2 Al	DOP, 0°	234	1.00	1.67
118 ± 3 Al	BL, 60°	328	1.00	1.33
Alumina on RHA, DOP				
20 AO /37 ± 1 RHA	DOP, 0°	362	0.65	1.08
30 AO /26 ± 1 RHA	DOP, 0°	313	0.75	1.25
Aluminium on RHA, Ballistic Limit				
20 AO /42 ± 2 RHA	BL, 60°	401	0.82	1.09
30 AO /32 ± 2 RHA	BL, 60°	360	0.91	1.21
40 AO /24 ± 2 RHA	BL, 60°	334	0.98	1.31
60 AO /12 ± 2 RHA	BL, 60°	314	1.05	1.39
80 AO /6 ± 2 RHA	BL, 60°	340	0.96	1.28
Silicon Carbide on Aluminium, DOP				
20 SiC /49.2-56.5 ± 2 Al	DOP, 0°	201-221	1.17-1.06	1.94-1.76
30 SiC /32 ± 2 Al	DOP, 0°	185	1.27	2.11
45 SiC /2.7 ± 2 Al	DOP, 0°	152	1.54	2.57
Silicon Carbide on Aluminium, Ballistic Limit				
10 SiC /94 ± 3Al	BL, 60°	293	1.12	1.49
20 SiC /80 ± 3 Al	BL, 60°	286	1.15	1.53
40 SiC /44 ± 3 Al	BL, 60°	250	1.31	1.75
65 SiC /13.4 ± 3 Al	BL, 60°	245	1.34	1.78
Alumina on Aluminium, DOP				
20 AO /58 ± 2 Al	DOP, 0°	235	1.00	1.66
30 AO /44 ± 2 Al	DOP, 0°	232	1.01	1.68
Alumina on Aluminium, Ballistic Limit				
20 AO /86 ± 3 Al	BL, 60°	312	1.05	1.40
40 AO /56 ± 3 Al	BL, 60°	302	1.08	1.44
60 AO /40 ± 3 Al	BL, 60°	331	0.99	1.32
80 AO /16 ± 3 Al	BL, 60°	338	0.97	1.29

Table 3. DOP and ballistic limit data at 2200 ms^{-1} ($\Delta v_P = \pm 40\ ms^{-1}$)

Target LOS [mm]	Test Method	$\rho_{A\ tot\ (LOS)}$ [kg/m^2]	MEF $_{SYS-Al}$	MEF $_{SYS-RHA}$
RHA Baseline, 2200 ms^{-1}				
89 ± 1 RHA	DOP, 0°	694	0.67	1.0
97.4 ± 2 RHA	BL, 60°	760	0.72	1.0
Aluminium Baseline, 2200 ms^{-1}				
166.5 ± 2 Al	DOP, 0°	463	1.0	1.50
198 ± 3 Al	BL, 60°	550	1.0	1.38
Silicon Carbide on Aluminium, DOP, 2200 ms^{-1}				
40 AO /94.5 ± 2 Al	DOP, 0°	410	1.13	1.69
60 AO /64 ± 2 Al	DOP, 0°	398	1.16	1.74
80 AO /24 ± 2 Al	DOP, 0°	360	1.28	1.93
Alumina on Aluminium, Ballistic Limit, 2200 ms^{-1}				
20 AO /163 ± 3 Al	BL, 60°	527	1.04	1.44
40 AO /128 ± 3 Al	BL, 60°	503	1.09	1.51
60 AO /102 ± 3 Al	BL, 60°	504	1.09	1.51
80 AO /72 ± 3 Al	BL, 60°	494	1.11	1.54
100 AO /36 ± 3 Al	BL, 60°	467	1.18	1.63
120 AO /8 ± 3 Al	BL, 60°	463	1.19	1.64

Table 4. Optimal ballistic limit target compositions

Target LOS [mm]	Impact Velocity ms^{-1}	Areal density $\rho_{A\ tot\ (LOS)}$ kg/m^2	Improvement over baseline (% reduction in $\rho_{A\ tot\ (LOS)}$)	Thickness ratio T_{cer}/T_{met}
118 ± 3 Al (reference)	1450	328	0	-
40 AO /24 ± 2 RHA	1450	314	4	1.7
40 AO /56 ± 3 Al	1450	302	8	0.7
65 SiC /13.4 ± 3 Al	1450	245	25	4.9
198 ± 3 Al (reference)	2200	550	0	-
120 AO /8 ± 3 Al	2200	463	16	15.0

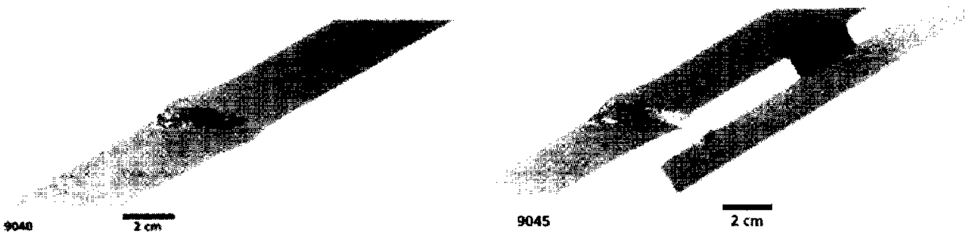

Fig. 4. Examples of non-perforated and perforated targets.

The non-perforated target is 20 SiC / 24 Al at 1450 ms^{-1}.The perforated target is 20 SiC / 20.4 Al at 1450 ms^{-1}.

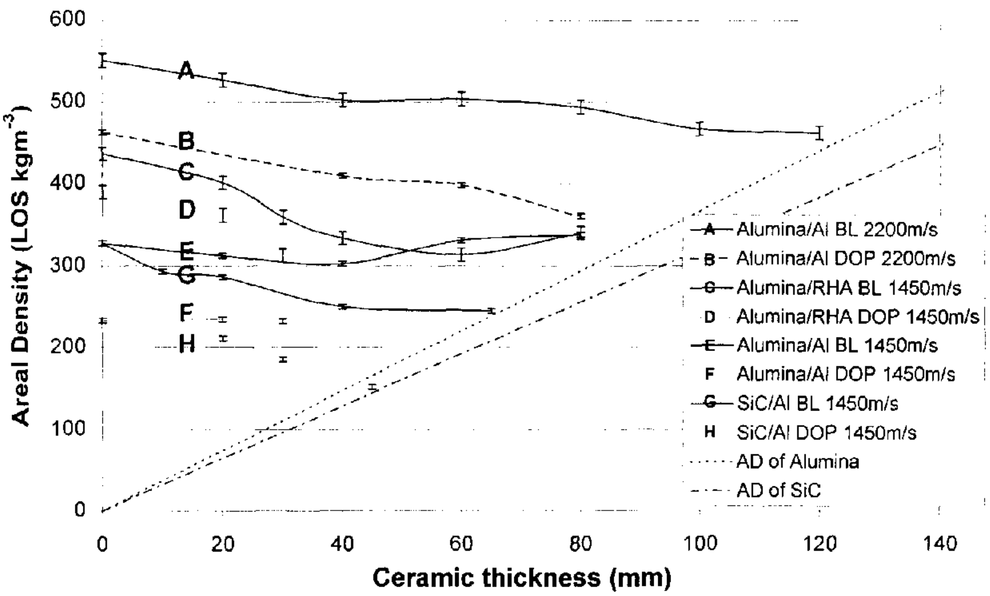

Fig. 5. Total areal density required to defeat the penetrator

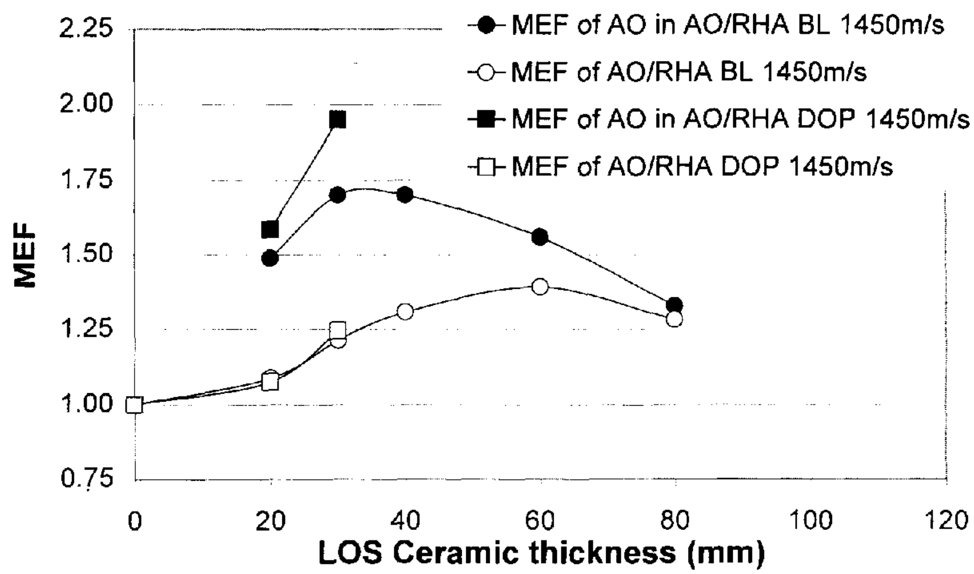

Fig. 6. Alumina on RHA at 1450ms^{-1}

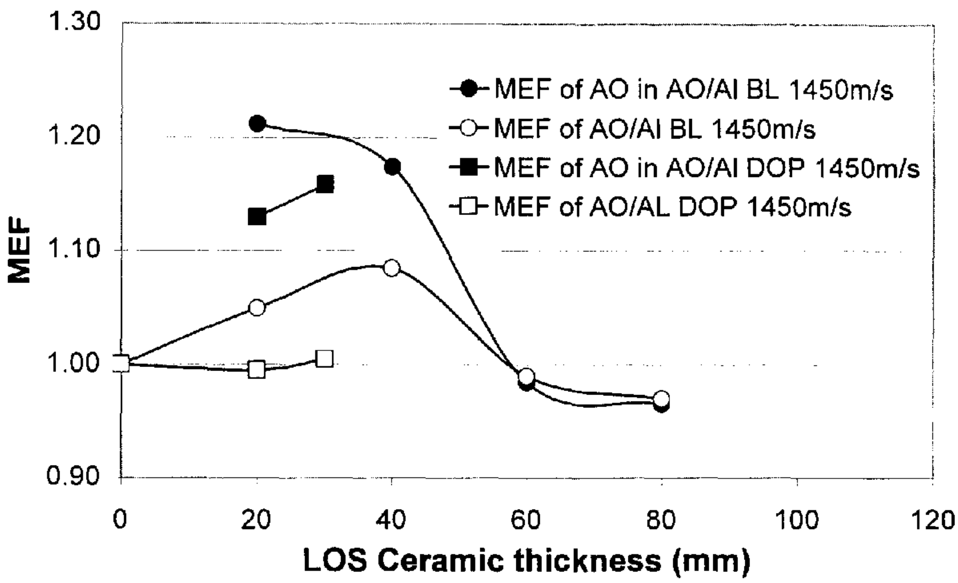

Fig. 7. Alumina on Aluminium at 1450 ms^{-1}

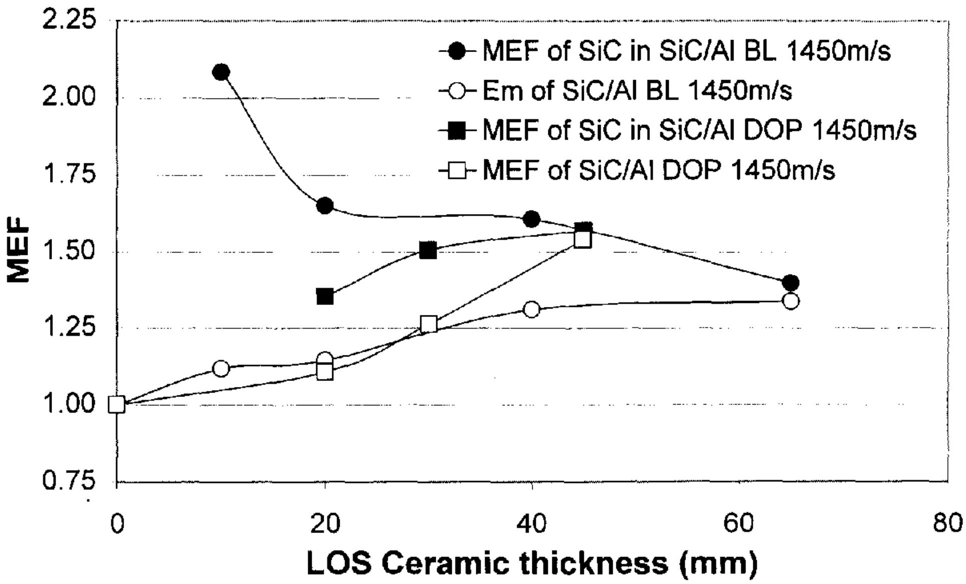

Fig. 8. Silicon Carbide on Aluminium at 1450 ms^{-1}

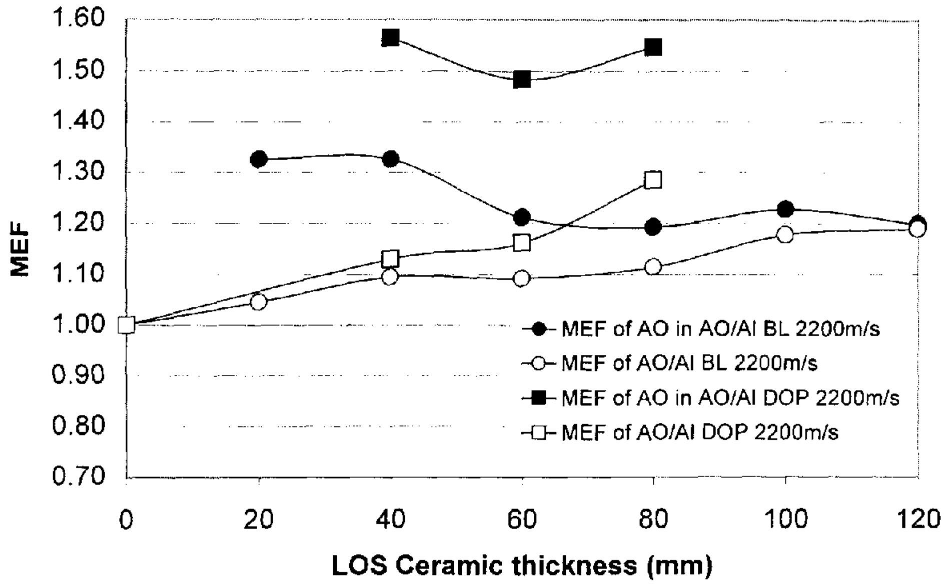

Fig. 9. Alumina on Aluminium at 2200 ms^{-1}

DISCUSSION

The hardness of the aluminium substrates was largely invariant at about 160 $Hv_{,50kg}$. However, the hardness of the RHA plates used varied with the plate thickness, from 310 $Hv_{,50kg}$ for plate thickness greater than 13 mm up to 385 $Hv_{,50kg}$ for thinner plates. Although this is a significant increase in hardness, the thin plates formed only a small part of the metallic fraction and, therefore, of the overall target (mainly ceramic) and so the effect on performance is deemed to be small.

The optimal ceramic/backing thicknesses have been determined for each of the four oblique ballistic limit targets. These are shown in Table 4. The mass savings over the reference target clearly rank the performance of the different ceramic/metallic combinations. AO/RHA is the least efficient, AO/Al is slightly better, and SiC/Al performs the best with a weight saving of 25%.

Figure 5 shows, as expected, the lower areal density of penetrated target material in the DOP tests, compared to ballistic limit targets. DOP areal densities appear to decrease linearly to a minimum when zero penetration into the semi-infinite backing occurs. The ballistic limit curves closely follow the DOP trends with an offset, until the ceramic content reaches approximately 66% of the system mass. The efficiency of these systems then diminishes since the backing plates offer less support through bending, due to their reduced thickness. At this point the ballistic limit results deviate from the trend, and in some cases form a minimum before the ceramic phase saturates the target composition. These minima arise, for example for AO/Al at 1450ms^{-1}, because the performance of the ceramic is only marginally better than the substrate, and therefore cannot compensate for the drop in performance of the backing plate. When the ceramic performance is significantly better than that of the substrate, for example SiC/Al, AO/RHA and AO/Al at 2200ms^{-1}, the maximum performance is attained at ceramic saturation, because the additional ceramic compensates for the reducing efficiency of the back plate.

The MEF_{SYS} values in Figure 6 to Figure 9 reflect the results of Figure 5. MEF (DOP) increases with the ceramic LOS and achieves the maximum value for zero penetration into the semi-infinite backing. The MEF_{CER} values for alumina based, ballistic limit targets consistently demonstrate a peak in performance of the ceramic phase at about 30 to 40mm LOS thickness. For AO/RHA and AO/Al at 1450ms^{-1}, this effectively corresponds to a peak in system performance as well. The improvement in performance seen as the alumina thickness is increased from 20 to 40 mm is probably due to an increase in the time taken for release to arrive from the rear surface of the ceramic phase. This would reduce the rate of damage accrual, maintaining penetration resistance for a longer period. However, the ceramic performance decreases with further thickness increase because backing plate flexure reduces axial confinement, which consequently decreases the penetration resistance of the ceramic.

For impact at 2200 ms^{-1} on AO/Al, a local peak also exists at about 40mm ceramic thickness. The performance of the ceramic is significantly greater for such a high velocity impact and is less influenced by the support of the backing. The system performance increases roughly as a 'rule of mixtures' (i.e. System MEF ≈ 1/(fraction of ceramic/MEF of ceramic + fraction of aluminium/MEF of aluminium)) as the ratio of ceramic to aluminium increases.

MEF_{CER} values for impact against oblique SiC/Al ballistic limit targets at 1450ms^{-1} show a rapid initial degradation from a high performance of the ceramic phase as the LOS thickness is increased from 10 to 20mm. This is unlikely to be due to increasing backing plate flexure since the thickness is still greater than 80mm LOS. Furthermore, the ballistic limit MEF results show a different profile to the DOP results, which are conducted at normal obliquity. It seems likely that the high performance of the ceramic in this instance is an angle effect, which may enhance the tendency for partial dwell to occur. This degree of partial dwell may be the same for all thicknesses but the efficiency is more notable at thinner sections.

There is little information available in the literature that bears direct comparison with the oblique impact results obtained in this work. It is interesting to note, however, that the optimum system response seen in the alumina/aluminium system for a ceramic thickness of 40mm (Aluminium = 56mm) shows similarity with results obtained by other workers and by other work performed by two of the authors.

Hetherington [21] refers to work by Ali [22] showing an optimum ceramic thickness, in the ballistic limit configuration, for the defeat of 7.62mm AP rounds impacting alumina/aluminium systems at ~850 ms^{-1}. The latter showed experimentally that maximum ballistic limit velocity was obtained for a ceramic/metal plate thickness ratio, T_{cer}/T_{met}, of 1.5 for normal impact (V_{BL} = 850 ms^{-1}), reducing to 1.0 for 30° obliquity.

Hohler, Stilp and Weber [16] use a somewhat more complex target structure, incorporating a thin RHA and rubber front layer. However, their results using an 8.2mm diameter tungsten sinter alloy rod, with an enlarged central section, impacting at 1500 ms^{-1}, give optimum thickness ratios, T_{cer}/T_{met}, of approximately 2.0 at 0° obliquity, 1.25 at 45° obliquity, and 0.82 at 60° obliquity.

Our results show an optimum performance for a ceramic/metal plate thickness ratio of 0.71 for alumina on aluminium at 60° obliquity and at 1450 ms^{-1}. This value is very similar to that obtained by Hetherington and by Hohler, Stilp and Weber. The latter similarity is not surprising as the impact conditions were similar. The similarity of our T_{cer}/T_{met} ratio with that of Hetherington is, however, quite surprising given the difference in impact conditions. We show in Table 4, that the optimum T_{cer}/T_{met} ratio is highly dependent upon the impact conditions. It can be seen that this ratio changes to 1.7 for Al_2O_3/RHA at 1450 ms^{-1} and 60° obliquity, to 4.9 for SiC/Al at 1450 ms^{-1} and 60° obliquity and to a ratio of 15.0 for SiC/Al at 2200 ms^{-1} and 60° obliquity. The ratio is thus seen to change substantially with impact conditions. This ratio is an indicator of the relative performance of the ceramic and metal fractions, and our results support the findings that aluminium has a higher MEF than RHA, SiC has a higher MEF than Al_2O_3, and that the performance of the ceramic increases with impact velocity.

An often used 'Rule of thumb' in the design of armour systems is that the hard ceramic front layer should contain 2/3 of the system mass whilst the supporting back layer contains 1/3 of the mass. For an alumina/aluminium system, this mass ratio results in a thickness ratio, T_{cer}/T_{met}, of approximately 1.5, agreeing with the values above for normal impact at the lower velocities. A more useful approximation to the optimal thickness ratio has been devised by fitting the, admittedly sparse, available data to the following simple equation:

$$T_{cer}/T_{met}\ (optimum) = \frac{Velocity}{59{,}791}\ x\ (90 - Impact\ \ angle) \qquad (3)$$

This equation gives the following results:

Table 5 Optimum thickness ratio for alumina/aluminium armour systems

Velocity ms^{-1}	Impact Angle degrees	Experimental Optimum Ratio T_{cer}/T_{met}	Optimum Ratio From Equation 3	Source
850	0	1.5	1.28	Ref. [21]
850	30	1.0	0.85	Ref. [21]
1450	60	0.71	0.73	This work
1500	0	2.0	2.26	Ref. [16]
1500	45	1.25	1.13	Ref. [16]
1500	60	0.82	0.75	Ref. [16]

CONCLUSIONS

The optimal configuration of ceramic/metallic bilayer targets, impacted at 60° obliquity have been determined via a parametric study. The test procedure entailed firing model scale tungsten penetrators at 1450ms^{-1} and 2200ms^{-1} at angled targets to determine the ballistic limit of the metallic backing as a function of ceramic thickness. The investigation used two ceramics, alumina and silicon carbide, and two metallic backings, RHA steel and aluminium, in various combinations.

At 1450ms^{-1} the most efficient system was found to be a SiC/Al, which demonstrated a 25% weight saving over the monolithic aluminium reference target. Next in order of rank was Al_2O_3/Al (8% weight saving) followed by Al_2O_3/RHA (4% weight saving). For the higher velocity of 2200ms^{-1} only one system was tested, Al_2O_3/Al, which showed a 16% saving in mass compared to the reference target.

Where the intrinsic ceramic performance is significantly better than the metallic backing, the maximum target performance is achieved with very thin backing plates, i.e. almost 100% ceramic. Where the performance difference between ceramic and backing is marginal (e.g. Al_2O_3/Al at 1450ms^{-1}), maximum performance is seen before the overall target response is degraded by flexure of the backing plate as a result of reduced thickness.

Although maximum performance is seen with high proportions of ceramic, in practice the returns in performance by employing more than 40mm of ceramic are minimal, and from a cost point of view this would seem to be the optimal thickness. Under the reported test regime and at this thickness the alumina ceramic and probably the silicon carbide operate at their most efficient.

The optimal ceramic thicknesses reported here are consistent with results found by other authors for similar systems.

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