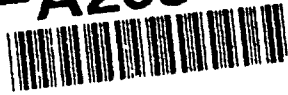


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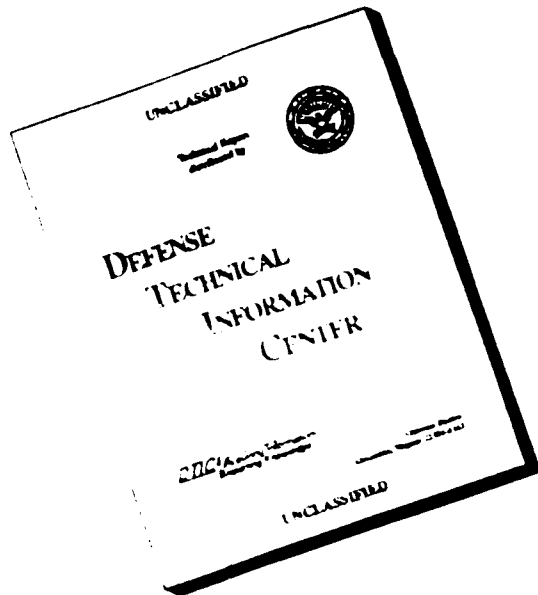
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EFFECTS OF CERAMIC TYPE ON FRAGMENTATION

BEHAVIOUR DURING BALLISTIC IMPACT

13th International Symposium on Ballistics
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This work reports experiments in which different grades and types of ceramic are impacted by tungsten alloy projectiles, and the resulting debris is analysed to assess the influence of ceramic properties on the degree of fragmentation and the distribution of cracking in the ceramic. The experiments utilize two grades of titanium diboride, four grades of alumina, as well as toughened zirconia tiles and glass. Toughness is seen to have a large influence on tile fragmentation, with the very tough zirconia tiles showing significantly less breakup, and the brittle glass showing excessive fragmentation. Whilst a correlation is established between toughness and degree of fragmentation, for small differences in toughness ($\sim 2\text{MPa m}^{1/2}$) the shot to shot variation in fragmentation can obscure that relationship. For two cases, glass and AD85 alumina, the projectile did not deform and this allowed calculations of the mean pressure resisting penetration.

INTRODUCTION

The perforation of a ceramic by a projectile involves penetrator tip fracture and penetrator erosion, loading of the ceramic, ceramic fracture and continued loading of the rubble bed, momentum transfer to, and ejection of, the ceramic debris, and stress wave propagation and interaction within the ceramic and the confining structure. The complexity of these concurrent processes makes it difficult to isolate key parameters which determine performance, measured as resistance to penetration. Previous studies of the interaction between projectiles and ceramic targets have highlighted aspects of modelling [1-4], energy distribution [5-8], ceramic fracture [6-11], and ballistic performance assessment [12-15]. Ceramic fragmentation is important because a large proportion of the projectile kinetic energy is redistributed as kinetic energy of ejected ceramic particles [5-8], however toughness itself is not found to be an indicator of performance [6,9].

In earlier work on confined and unconfined alumina ceramics it was demonstrated that the size distribution of fragmented ceramic was consistent with two mechanisms of fracture viz. (a) comminution in the path of the advancing projectile producing the majority of the fine fragments, some of which are ejected at high velocity, and (b) fracture by stress wave interactions, away from the projectile path, resulting in coarser, lower velocity fragments. The present work extends those previous studies by examining the shot to shot consistency of the debris distribution, and by the inclusion of both non-oxide and very tough ceramics. In addition the debris size distribution is examined in more detail.

EXPERIMENTAL METHODS

The details of ceramic confinement and lay-up, the ballistic testing and analysis techniques were fully described in the earlier work [8]. As in that case, unconfined targets consist of a tile bonded to a 6.35mm aluminum alloy backing. Confined targets consist of a tile bonded to a 38mm aluminum alloy backing plate with additional such plates placed behind this back to back, and the impact side covered by a 6.35mm aluminium alloy plate. In both confined and unconfined cases the tiles were surrounded by a close fitting steel jacket.

As well as carrying out further firings against the AD90 and AD995 aluminas used in the previous work, two brands of TiB_2 (Ceradyne and Cercom), a toughened zirconia (Nilera MS grade ZrO_2) and a soda lime glass, were tested. The earlier results on AD85 and AD96 alumina tiles are also included for comparison. All tiles were 100mm square and 12.7mm thick except for the zirconia which was 10mm thick and the glass which was 15mm thick. Tile physical and mechanical properties are listed in Table 1.

TABLE 1
TILE PHYSICAL AND MECHANICAL PROPERTIES

Ceramic	Density	Elastic Modulus	Toughness K_{Ic}	Compressive Strength	Hardness (Diamond Pyramid) (GPa)
	($kg\ m^{-3} \times 10^3$)	(GPa)	($MPa\ m^{3/2}$)	(MPa)	
AD85	3.43	224	3.2	2175	8.8
AD90	3.58	268	3.3	2345	10.6
AD96	3.74	310	3.7	2660	12.3
AD995	3.90	383	4.7	2785	15.0
TiB_2 (Ceradyne)	4.52	414	4.1	~5700	27.0
TiB_2 (Cercom)	4.52	538	5.2	~6000	26.1
ZrO_2 (Nilera, MS)	5.72	205	12.	1990	11.2
Soda Lime Glass	2.5	69	0.73	966	5.5

Using the procedures described in earlier work [8] recovery of ceramic debris was better than 99% of the original tile mass. On disassembly of impacted confined targets, the debris from within the fracture conoid was separated from the ceramic outside the conoid, and its size distribution determined separately. This was also done for the ejected debris. Because of the difficulty of containing broken fragments with the unconfined targets, the analysis of fragment distributions from different sections of these targets was less successful.

RESULTS AND DISCUSSION

(a) Toughness and Fragmentation

Figure 1 illustrates dramatically the influence that large differences in toughness can have on the volume of fragments in any size range of the fragment distribution, by plotting the volume of fragments in a size range against size for confined targets of glass, AD995 alumina and zirconia. The slightly different thicknesses of the glass and zirconia tiles do not influence the general conclusions to be drawn from this data.

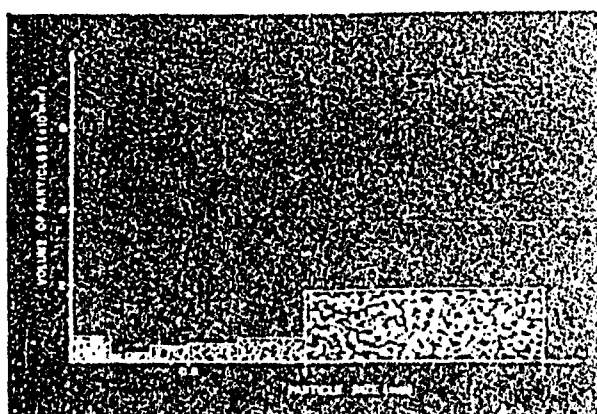
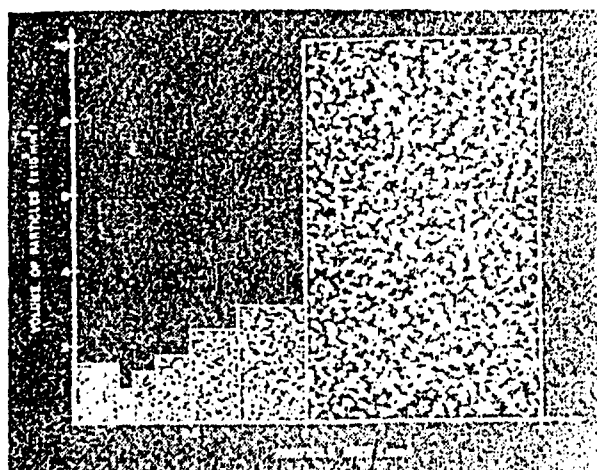
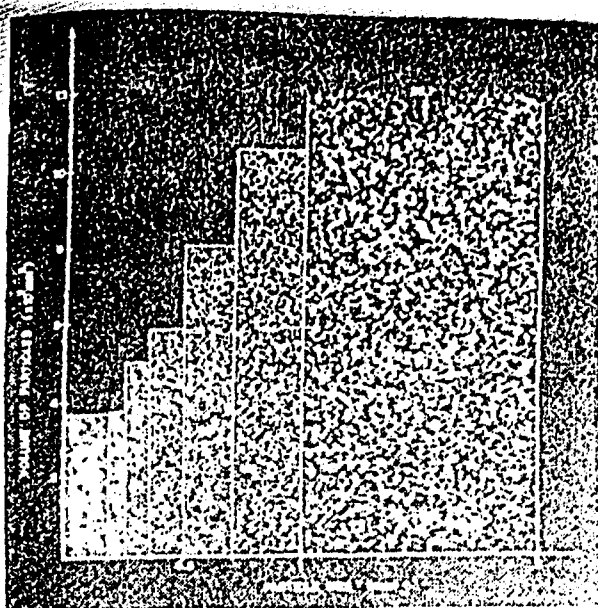


Fig.1

Volume of fragments plotted against fragment size for (top to bottom) glass, AD995 alumina and zirconia. The fragment size is indicated by the typical fragments in each size fraction. The total volume of the glass tile was 18% greater, and that of the zirconia 27% smaller, than the alumina tile.

Figure 2 shows cumulative fragment volume against size for confined and unconfined targets respectively. These plots indicate a general correlation between an increased volume of fragments produced and a lower ceramic fracture toughness. However within the band of results covering those ceramics considered for armour applications (aluminas and TiB_2), where toughness ranges from 3.2 to 5.6 MPa $m^{1/2}$, there are contradictions to this general rule, and the ordering of results also varies with the size range. As in the earlier work [8], the use of volume of fragments in any size range allows a direct comparison between ceramics of different density, the volume being calculated simply by dividing the mass of that fraction by the material bulk density. Comparison of repeat shots for AD90 and AD995 indicates that a significant shot to shot variation in the total number of fragments in each size fraction is possible (of the order of 25%). The shot-to-shot variation in tile fragmentation is a combination of reproducibility of the target construction (particularly degree of confinement), variations in impact conditions, tile-to-tile variations in ceramic fracture behaviour, and variations in projectile shatter. Both confined shots against AD995 involved negligible yaw and produced similar residual penetrations into the backing (45 and 44 mm) and yet there is a substantial difference in tile fragmentation.

The simple model proposed in earlier work [8] for explaining ceramic break-up features would have the fine fragments occurring in a "penetration column" along the line of projectile flight and ejected as penetration proceeds, with the coarser fragments being produced in the distal regions of the tile by stress wave interactions. As an approximation, the fracture conoid is easily separated from the distal fragments and when it is combined with ejecta fragments this should account for the majority of fine fragmentation.

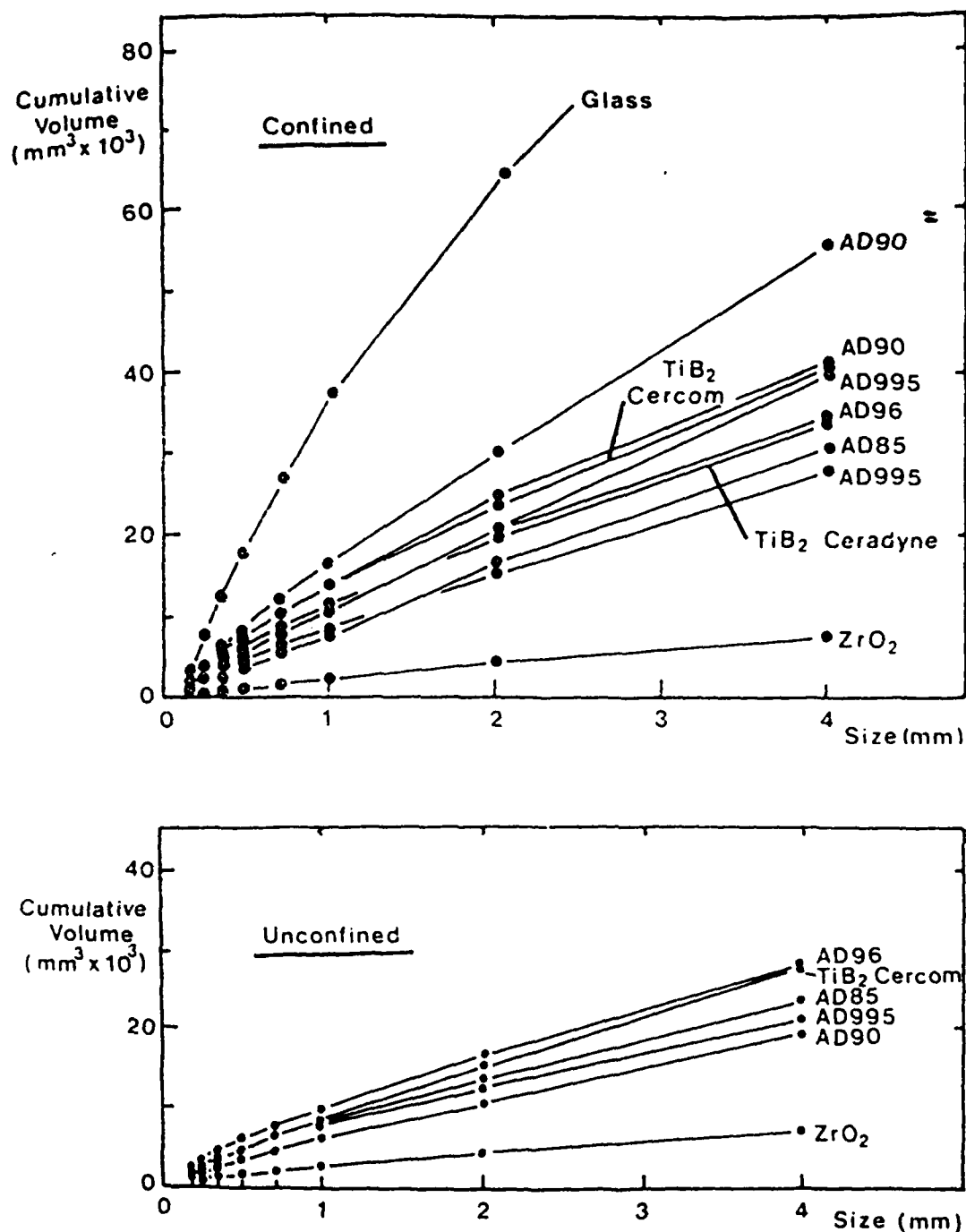
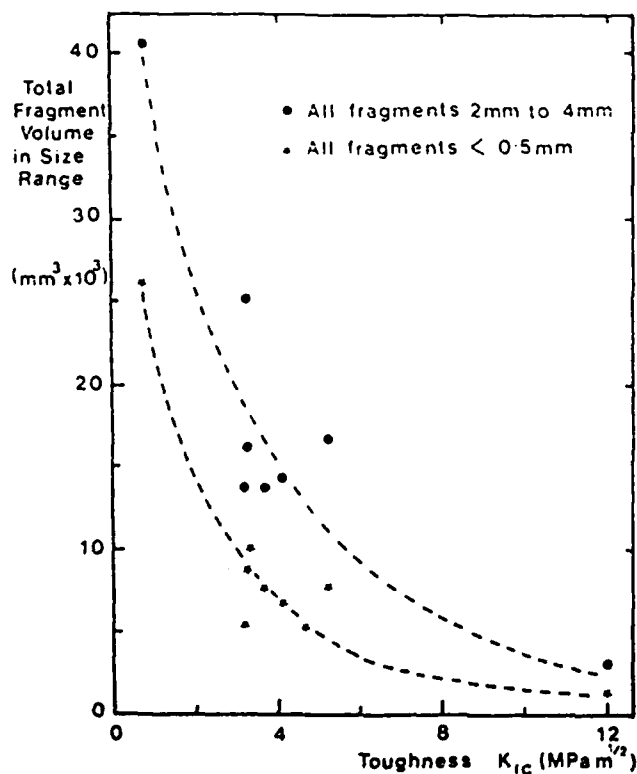


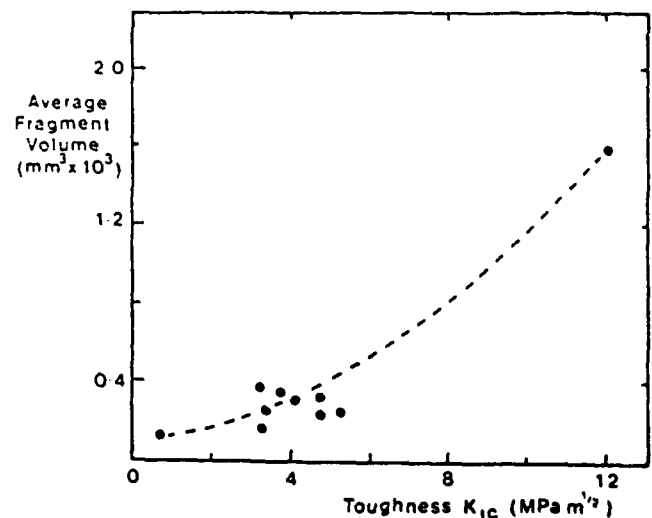
Fig.2 Cumulative volume of fragments as a function of fragment size for confined targets (top) and unconfined targets (bottom).

In all cases it was found that greater than 60% of the fine fragments occur within the conoid, and the percentage generally drops as fragment size increases. The zirconia has an extremely high proportion of fine fragments within this region, even fragments up to 4mm in size being mostly produced within the conoid. Very few of the large fragments (>4mm) are produced within the conoid. This latter phenomenon is partly due to the fact that the conoid itself is only a proportion of the total volume of a tile, and largely due to the fact that these coarser fragments are produced by tensile relief waves whereas those in the line of projectile flight are produced by crushing. In the cases where targets were shot in both confined and unconfined configurations, the present results confirm an earlier observation [8] that a greater volume of the coarser fragments occur for confined targets and with two exceptions (AD90 and Cercom TiB₂) the unconfined targets show a greater volume of the very fine fragments.

To further explore the correlation between degree of fragmentation and toughness, the volume of fragments is plotted against toughness in Figure 3(a) for the confined targets, for all fragments less than 0.5mm, and for fragments in the size range 2 to 4mm. Overall there is a clear inverse relationship which conforms with earlier work [6,9]. For the region beyond the cone it would be expected that lower toughness would lead to increased fragmentation and this was assessed approximately by counting the total number of fragments greater than 4mm in dimension. As expected the zirconia had the smallest number of large fragments, however the glass produced similar numbers of large fragments to both the alumina and TiB_2 ceramics because it was so brittle that even outside the fracture conoid, breakup is severe producing a predominance of fine fragmentation. In Figure 3(b) is plotted the average volume of the fragments greater than 4mm in size against toughness for each material. Given that a 4mm cube has a volume of 64mm^3 then the average large glass fragment is only twice that size. Again there is a reasonable correlation with toughness. The trends in both Figures 3(a) and 3(b) rely on a single data point for the very tough zirconia ceramic, a single point for the very brittle glass, and a group of points for all the alumina and TiB_2 tiles. This emphasises that the variation in fragmentation behaviour arising from small differences in toughness is masked by the shot to shot consistency of results, as is also evident from Figure 2.



(a)



(b)

Fig.3.(a) Total volume of fragments in size fractions $<0.5\text{mm}$ and 2 to 4mm plotted against fracture toughness, K_{IC} , for the confined targets. (b) Plot of the average volume of a fragment for those fragments $> 4\text{mm}$ in dimension against ceramic fracture toughness, K_{IC} .

(b) Penetration Resistance

The resistance to penetration of the ceramics compared with aluminum can be ranked using a ballistic efficiency parameter, η , defined by Rozenberg and Yesherun [13] as

$$\eta = \frac{\rho_{A1} \Delta h_{A1}}{\rho_c h_c} \quad (1)$$

where ρ_{A1} and ρ_c are the densities of aluminum and ceramic respectively, h_c is the ceramic tile thickness, and Δh_{A1} is the reduction in thickness of aluminum penetrated when the ceramic tile is in place.

These data are given in Table II for the glass and AD85 alumina, for both of which the projectile did not deform, and for the AD995 where the projectile was fractured. All the other ceramics gave similar residual depths to the AD995. The relative ballistic efficiencies are in order of strength.

TABLE II
BALLISTIC EFFICIENCY AND PENETRATION RESISTANCE

Material	Ballistic Efficiency (Eqn.1) (η)	Hardness (Diamond Pyramid) (GPa)	Mean Pressure Resisting Penetration (GPa) (Eqns.2&3)	Impact Pressure (GPa)(Eqn.4)
Aluminum	-	1.03	1.39	-
Glass	4.2	5.5	5.4	13.4
AD85	8.6	8.8	15.2	24.2
AD995	11.7	15.0	-	30.3

From the penetration into aluminum a mean resisting pressure, P_{A1} can be calculated using

$$\frac{1}{2}mv^2 = P_{A1} A h_{A1} \quad (2)$$

where the first term is the projectile impact kinetic energy (mass m , and impact velocity v),

A is the presented area of the projectile, and

h_{A1} is the depth of penetration into the aluminum block

Similarly, using this value of P_{A1} a value can also be found for the mean pressure resisting penetration into the ceramic, P_c , using

$$\frac{1}{2}mv^2 = P_c A h_c + P_{A1} A h'_{A1} \quad (3)$$

where h_c is the ceramic tile thickness, and

h'_{A1} is the residual depth of penetration into the aluminum.

The results of these calculations are given in Table II for comparison with hardness (Diamond Pyramid) and with impact pressure calculated from the simple elastic equation,

$$P = \frac{\rho_1 C_1 \rho_2 C_2}{\rho_1 C_1 + \rho_2 C_2} v_0 \quad (4)$$

where ρ and C are the density and wave speed respectively in two impacting solids, 1 and 2, and v_0 is the impact velocity.

The values presented in Table II raise more questions than they answer. It may be anticipated that the resistance to penetration by a projectile is related to the material hardness, which is a measure of its resistance to a blunt indenter. If fracture occurs, then resistance to penetration may be expected to be lower because of the reduced ability of fractured material to support shear stresses. In addition, the requirement to increase the momentum of the ceramic material which is being rapidly displaced or ejected may increase this resistance to penetration in proportion to the impact velocity. The pressure with which the aluminum resists penetration is of similar magnitude to its hardness. The mean resistance provided by the glass is also similar to the hardness, however in this case it is surprising because fracture would be expected to reduce the effective strength of the glass. Whilst the value of 5.4 GPa in Table II for glass is expected to be made up of a component overcoming the material strength and a component to increase the momentum of the glass, the magnitude of the individual contributions is uncertain. Pavel et al. [16] present data for penetration of thick glass specimens by a non-deforming projectile at 1060 ms^{-1} , and analysis of this data indicates an average resisting pressure of the order of 1.2 GPa, although numerical studies by Pavel et al. [16] showed that the actual pressure varies significantly during the event and can be much higher than this average value. The mean resisting pressure for AD85 alumina is much greater than its measured hardness. The calculated elastic impact pressures are in the correct order but, as expected, have no close relationship to the resisting pressure calculated from depths of penetration. No calculations of mean pressure resisting penetration were done for the AD995, or the other hard ceramics, as the fracturing of the projectile means the use of equations (2) and (3) is invalid without data on blunt projectile penetration into aluminum.

In penetrating the ceramic the projectile does work overcoming the strength of the material, and also in increasing the velocity of the ceramic in order to displace it. If the target was a metal then the work done in overcoming the strength of the material would appear principally as distortional strain energy and heat in proportions of approximately 5% and 95% respectively. Despite the high stress levels, the strains are small in brittle materials so that the conversion of work to heat cannot account for the work done on such a target. Previous studies [5,6,8] have concluded, on the basis of measured surface areas and fracture work, that the work of fracture is also insufficient to account for the work done in penetration of such a target. A reasonable hypothesis is that by elastic and shock wave reflections and interactions within the fragmenting material, the work done in overcoming the material strength also contributes to the increase in kinetic energy of the ceramic debris.

CONCLUSIONS

Fragmentation of ceramics under confined and unconfined conditions has been studied. The studies included non-oxide ceramics (TiB_2), very tough ceramics (zirconia) and very brittle materials (glass). The results indicate the shot to shot reproducibility of fragmentation data is of the order of 25% in volume of fragments. The results confirmed a correlation between toughness and degree of ceramic fragmentation, and they are consistent with an earlier suggestion that fine fragments are produced by comminution ahead of the projectile and coarser fragments are produced by the interaction of stress relief waves away from impact. For two cases in which the impacting projectile did not deform, glass and AD85 alumina, the results allow an average pressure resisting penetration to be calculated.

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