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Influence of Polymer Restraint on Ballistic Performance of Alumina Ceramic Tiles

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ABSTRACT

An experimental study has been carried out to evaluate the influence of confinement of alumina ceramic tiles through polymer restraint, on its ballistic performance. Tiles of 99.5 per cent purity alumina were subjected to ballistic impact against 7.62 mm armour piercing projectiles at velocities of about 820 m/s. The tiles of size 75 mm x 75 mm x 7 mm were confined on both faces by effectively bonding varying numbers of layers of polymer fabrics. These were then bonded to a 10 mm thick fibre glass laminate as a backing using epoxy resin. High performance polyethylene and aramid polymer fabrics were used in the current set of experiments for restraining the tiles. Comparative effects of confinement on energy absorption of tiles with varied number of layers of fabrics were evaluated. It was observed that by providing effective confinement to the tile, energy absorption could be doubled with increase in areal density by about 13 per cent. Photographs of the damage and the effects of restraint on improvement in energy absorption of ceramic tiles are presented and discussed.

Keywords: Alumina ceramic, ballistic impact, polymer fibres, confinement, projectile

1. INTRODUCTION

The application of ceramics as armour for protection against small arms threats has been growing. Efficiency of ceramic under ballistic impact varies with purity of ceramics, thickness as well as velocity of projectiles[1,2]. It has been continuously improved by adopting novel processing techniques, higher purity, and finer particle sizes, thereby achieving better mechnical properties and microstructures. Ceramic materials are capable of displaying significantly better energy absorption when confined. Confinement of ceramics improves the ballistic performance of ceramics by inhibiting various failure mechanisms[3]. Increase in efficiency of ceramic is also possible by lengthening the duration of dwell and the shattering stage of ceramic during the penetration process and also by increasing the erosion process of the projectile by efficiently engaging the comminuted ceramic in the process of interaction.

Lateral confinement provides constraint to the shattered ceramic debris which continues to interact with the projectile for a longer duration during the penetration and erosion process. Several methods have been developed to confine ceramic tiles under compressive deformation[4,5].

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Ballistic efficiency of a wide variety of ceramics has been studied by conducting depth of penetration experiments using thick backing[6,7]. Studies have also been carried out on perforation and fragmentation of confined and unconfined ceramic targets by pointed and blunt projectiles[8]. Attempts have been made in the recent past to improve the ballistic efficiency of alumina and *SiC* tiles by restraining them with layers of polymeric composites or metal sheets[9]. Improvement of about 25 per cent in energy absorption was obtained by restraining impact face of the tiles with layers of E-glass/epoxy, carbon/epoxy and *Ti*-alloy sheet for an increase in areal density of up to 3 per cent. Similar studies on restrained boron carbide tiles using varied number of polymeric composites (PMC) layers when backed by spectra shield showed improvements in efficiency by about 40 per cent for an increase in areal density of upto 9 per cent[10].

In the present work, an experimental study has been carried out to study the influence of confinement of high purity (99.5 %) alumina tiles by varying types of polymer fabrics on its ballistic performance. The confined tiles were subjected to ballistic impact of 7.62 mm armour piercing projectiles. A series of tests were conducted to study the improvement in energy absorption of a 7 mm thick alumina tile with and without confinement and the effect of varying the number of confining polymer layers. Results on the improvements in energy absorption of the configurations along with photographs of the damage morphology are presented.

2. EXPERIMENTS

2.1 Materials

Alumina tiles with 99.5 per cent purity were used as the ceramic target. Tiles of size 75 mm x 75 mm and thickness of 7.0 mm, having density of 3.92 g/cm^3 and mass of 153 g (areal density of 2.74 g/cm^2) were used. Two grades of commercially available fabrics were used for confining the ceramic tiles. One is the uni-directional HMWPE (Dyneema) having fibre tensile strength of 2.6 GPa and failure to strain of 3.5 per cent and the thickness of the fabric is 0.26 mm. The other is the aramid fabric (Twaron) having fibre tensile strength of 3.1 GPa and failure to strain of 2 per cent. These fibres are woven into plain weave fabric with warp and weft per 10 cm as 107 and having thickness of 0.3 mm. A 10 mm thick E-glass laminate was used as a standard backing plate for all the configurations. Tiles of 7 mm thick alumina were confined by wrapping 4, 6 and 8 layers of these fabrics.

2.2 Preparation of Ceramic Tiles with Polymer Fabrics

Ceramic tiles of 7 mm thickness were restrained by wrapping 2, 3 and 4 layers of each variety of polymer material in (0/90) configuration. Epoxy resin was first applied uniformly on the tile as well as on each layer of fabric so as to bond each of the layers to the tile using hand lay up. The final sample thus consisted of 4/6/8 layers of polymer fabrics. The sample was then placed in a sealed vacuum bagging and allowed to cure. This method was adopted to ensure uniformity of fabrication of all the samples as well as good restraint of the ceramic tile all around. These confined ceramic tiles were then bonded to a backing of 10 mm thick FRP laminate. Typical cross section of the confined ceramic tile is shown in Fig. 1. Details of the configurations used in the present set of experiments are given in Table 1.

2.3 Impact Tests

Ballistic tests were carried out by impact of 7.62 mm AP projectiles at velocities of 820 ± 10 m/s on all the configurations. Figure 2 shows the target holding set-up. The target was mounted in a steel

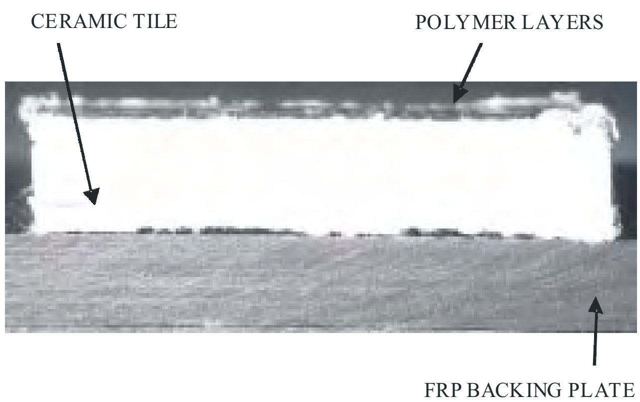


Figure 1. Cross-section of restrained ceramic tile.

Table 1. Restrained ceramic tile configurations used in the present experiments

Sample	Type of polymer fabric	No. of fabric layers	Fibre orientation	Areal density (g/cm^2)	Increase in areal density (%)
C0	None	Nil	Only tile	2.74	-
CD4	Dyneema	4	[0/90]	2.84	3.6
CD6	Dyneema	6	[0/90/0]	2.89	5.5
CD8	Dyneema	8	[0/90/0/90]	2.94	7.3
CT4	Twaron	4	[0/90]	2.91	6.2
CT6	Twaron	6	[0/90/0]	3.00	9.5
CT8	Twaron	8	[0/90/0/90]	3.09	12.8

frame that provided a uniform clamping restraint around the perimeter of the tile. The entire structure was then fixed to a target stand using C-clamps. The distance from the muzzle end of the gun to the target was kept at 10 m. Two velocity screens are placed before and after the target for measuring the striking and residual velocity of the projectile.

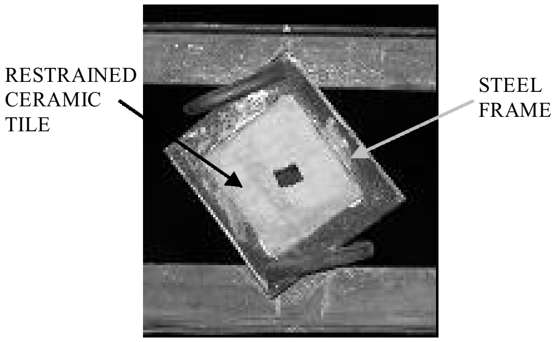


Figure 2. Typical target holding set-up.

Figure 3 shows the schematic diagram of ballistic experimental set-up. The mass of the projectile is 10.44 g with a hardened steel core weighing 5.2 g. These projectiles were fired from a standard sniper rifle in a small arms range at impact velocities about 820 m/s. The experimental results are given in Table 2. Residual velocity of the projectile with varying number of layers of fabric is plotted in Fig. 4. The projectile and target debris were collected for further investigations.

3. RESULTS

3.1 Ceramic Tile without Confinement

Bare alumina tile of 7 mm thickness backed by 10 mm thick FRP laminate reduced the velocity of the projectile by about 25 per cent. This result is the average of three data points with a mean scatter of about 2 per cent. This shows that the bare ceramic tile without any confinement absorbs about 44 per cent of the kinetic energy (E_{abs}). Shot was recovered after each test. Figure 5 shows photographs of original core of the projectile and typical core recovered after the test. It was observed that the shot broke and eroded during the penetration and the final mass of the recovered shot was found to be 3.1 g as compared to the original shot whose mass was 5.2 g. Most of the balance debris of the shot turned into very fine dust.

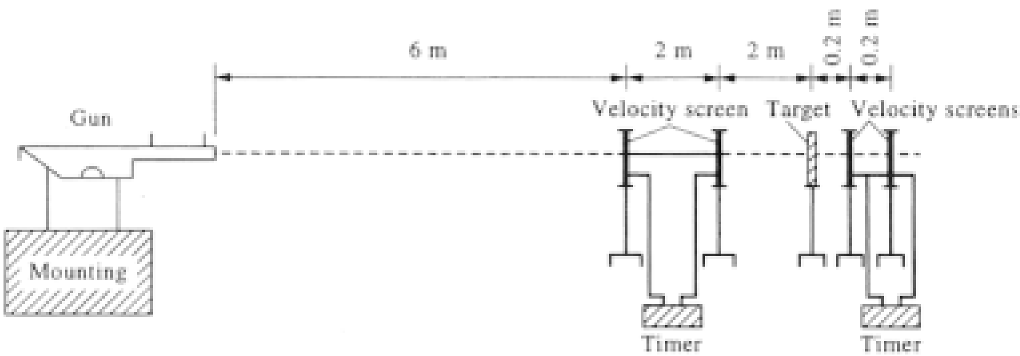


Figure 3. Experimental set-up.

Table 2. Ballistic impact results of restrained ceramic tiles

Sample	Increase AD (%)	Residual velocity (m/s)	E_{abs} (%)	Relative E_{abs}
C0	-	613	44	1
CD4	3.6	482	65	1.48
CD6	5.5	427	73	1.66
CD8	7.3	289	87	1.98
CT4	6.2	404	76	1.72
CT6	9.5	293	87	1.98
CT8	12.8	183	95	2.15

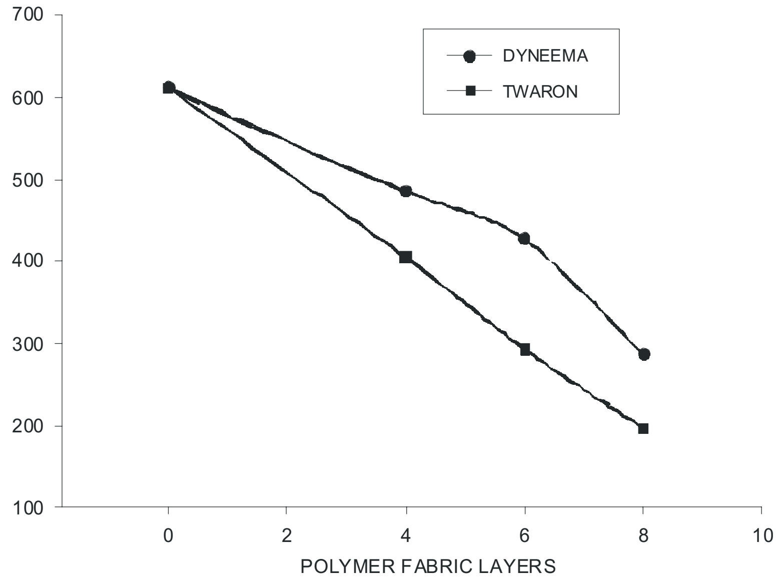
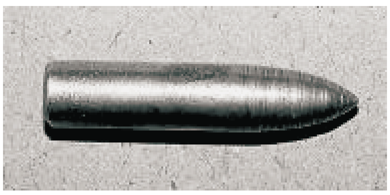
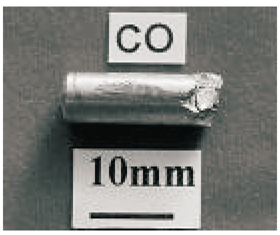


Figure 4. Residual velocity of the projectile with varying number of polymer layers.



(a)



(b)

Figure 5. Photographs of: (a) original shot and (b) recovered shot after perforation of bare tile.

3.2 Ceramic Tile Restrained with Dyneema Fabric

Tests were performed on tiles confined with 4, 6 and 8 layers of fabric distributed equally over the front and rear face of the tile. Figure 6 shows plots of kinetic energy absorbed by the target with increase in areal density. From the results, it is seen that amount of energy absorption increases with increasing number of polymer layers. Energy absorption for tiles restrained with 4, 6 and 8 layers of dyneema is found to be 65 per cent, 73 per cent and 87 per cent respectively. From the mass of recovered shots, it was observed that the residual mass of the projectile decreased from 3.1 g when impacted on bare tile to 2.91 g, 2.51 g and 2.43 g respectively with increase in confinement layers of dyneema. This is due to the fact that the

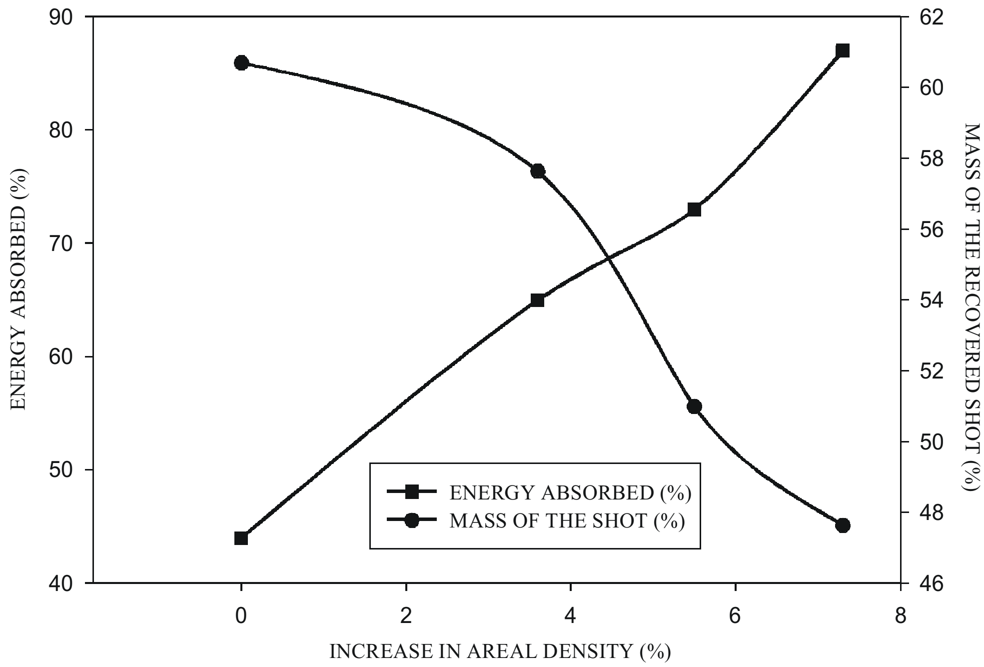


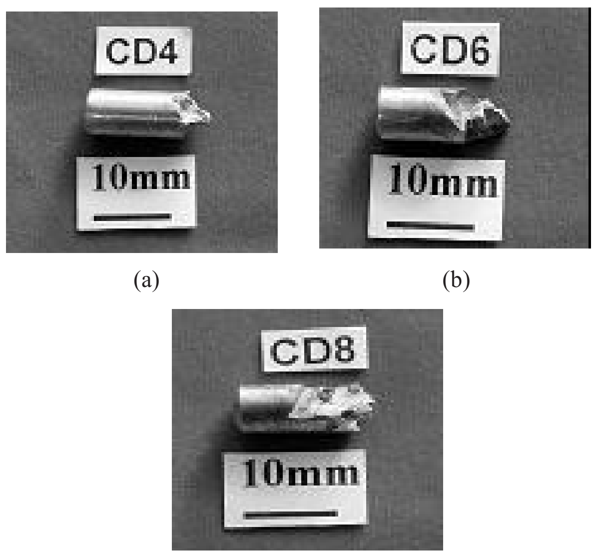
Figure 6. Effect of dyneema restraint on energy absorption and residual mass of the projectile.

duration of interaction increases with increasing the number of confinement layers, thereby increasing the amount of energy absorbed by the target.

It is also observed from the Table 2 that the residual velocity of the projectile decreased from 613 m/s in the case of bare tile to 482 m/s, 427 m/s and 289 m/s for tiles confined with 4, 6 and 8 layers of dyneema respectively. This indicates that there is an improvement in performance of 48 per cent, 65 per cent and 98 per cent respectively over bare ceramic tile for an increase in areal density of 3.6 per cent, 5.5 per cent and 7.3 per cent respectively. This indicates that the projectile encounters more amount of fracture as the number of restraint layers are increased. Figure 7 shows photographs of the typical recovered shots in all the three conditions of restraint.

3.3 Ceramic Tile Restrained with Twaron Fabric

Figure 8 shows the effect of confinement with increasing layers of twaron on energy absorption and residual mass of the projectile. Improvement in energy absorption of tiles restrained with twaron shows similar performance as in the case of dyneema restraint. It is found to be 76 per cent, 87 per cent and 95 per cent respectively. From the mass of recovered shots it is observed that the residual mass of the projectile decreased from 3.1g in the case of bare tile to 2.6 g, 2.2 g and 1.84 g for the tiles restrained with 4, 6 and 8 layers of twaron,



(a) (b) (c)

Figure 7. Photographs of recovered shots after perforation of dyneema restrained tile with: (a) 4 layers, (b) 6 layers, and (c) 8 layers.

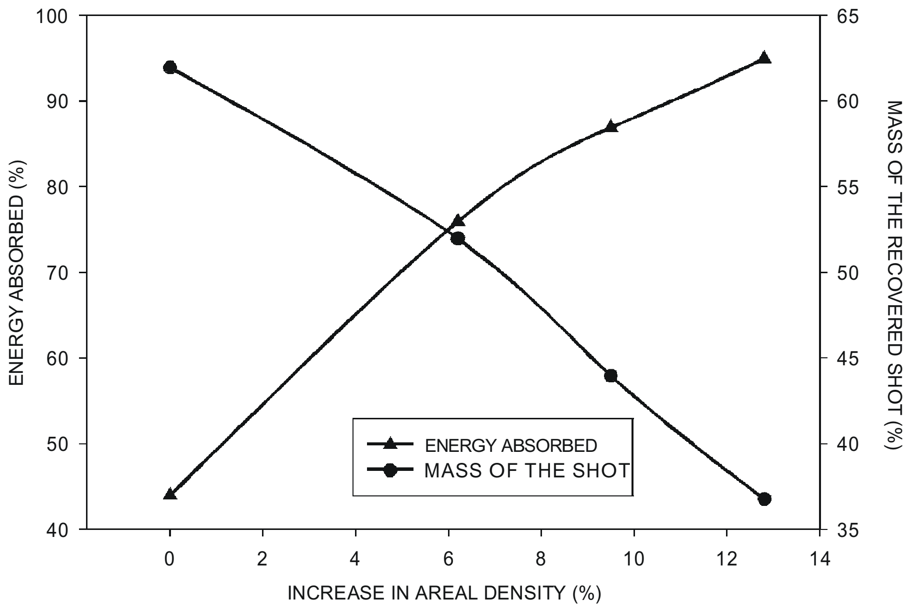


Figure 8. Effect of confinement of twaron layers on energy absorption and residual mass of the projectile.

respectively. The residual velocity of the projectile decreased from 613 m/s in the case of bare tile to 404 m/s, 293 m/s and 183 m/s respectively for restrained tiles. These results indicate that there is an improvement in energy absorption of 72 per cent, 98 per cent and 115 per cent respectively over bare ceramic tile without any confinement for a mere increase in areal density of 6.2 per cent, 9.5 per cent and 12.8 per cent respectively. Figure 9 shows the photographs of the recovered shots.

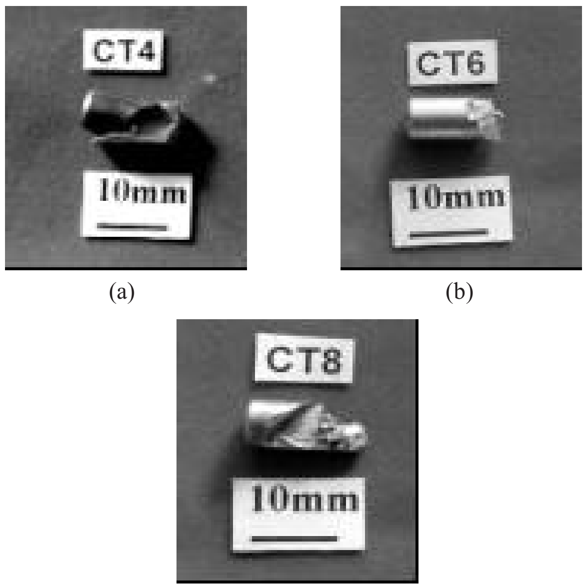
4. DISCUSSION

4.1 Increase in Energy Absorption

The results of the absorption in kinetic energy of the projectile for the different conditions of restraint are plotted in Fig. 10. These plots compare the improvement in efficiency of alumina ceramic tile when confined using varied number of layers of polymer membranes. From the plot, it is seen that the improvement in energy absorption of tiles confined by dyneema as well as using twaron are similar. Performance enhancement of more than double could be achieved by effectively confining the tiles.

4.2 Fragmentation of Ceramic Tile

In order to study the size distribution of fragmented ceramic tile after impact, fragments of both ceramic as well as the projectile were collected during each test by using a fragment collection chamber placed on the target. Fragments were separated from the target debris by using magnetic separation. Ceramic fragments were further segregated into different sizes by using sieve analyzer 70 μm to above 700 μm. The data is given in Table 3.



(a) (b) (c)

Figure 9. Photographs of recovered shots after perforation of twaron restrained tile with: (a) 4 layers, (b) 6 layers, and (c) 8 layers.

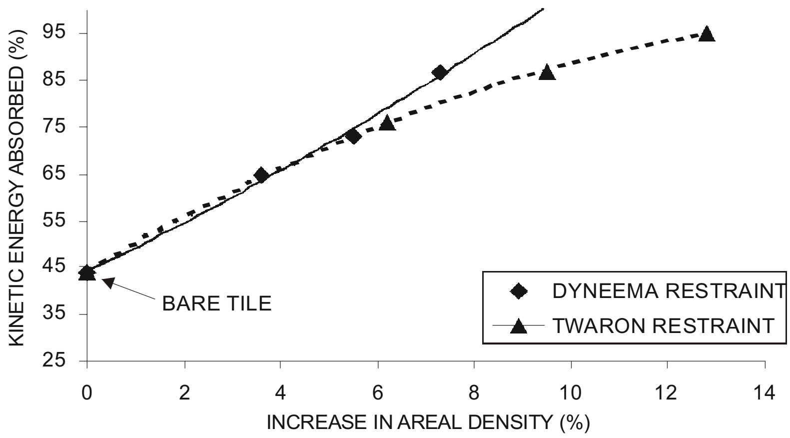


Figure 10. Improvement in energy absorption of tiles under restraint.

It is seen from the table that in the case of bare tile without restraint, the weight percentage of coarser fragments with size above 700 µm is about 94 per cent and all the finer size fragments in the range of 250-70 µm is about 6 per cent only. But in the case ceramic tile restrained with 4 and 8 layers of dyneema, the weight percentage of coarser fragments is about 81 per cent and 76 per cent, respectively and that of finer fragments is about 19 per cent and 24 per cent, respectively. Similarly in the case of twaron restraint, weight of the coarser fragments is about 67 per cent and 56 per cent respectively for restraint using 4 and 8 layers and the finer fragments in the range of 250 - 70 µm is about 33 per cent and 44 per cent respectively. It shows that as the number of confining layers increases, the weight percentage of finer fragments is increased. This indicates that under condition of restraint, the projectile interacts with the ceramic for a longer duration thereby generating more amounts of finer fragments. More amount of surface area of ceramic is generated which in turn absorbs more amount of energy for fragmentation.

4.3 Fracture of Ceramic Tile

In order to see the fracture behaviour of ceramic tile, fragments of different sizes were seen under scanning electron microscopy (model Leo440i). Prior to the scanning, palladium-gold sputter coating was applied on to the fragments to avoid charging. SEM pictures of the fragments of size of 700 µm, 150 µm and 70 µm are shown in Fig.11. From the photographs it is seen that in all the cases the ceramic tile is shattered into fine dust of up to 2 µm size. In all the fragments loose particles of fragmented ceramic are observed to be stuck on the surface. In the case of larger size (> 700 µm) the quantity of loose particles seems to be lesser. Mode of failure of ceramic is observed to be the same in all the fragments.

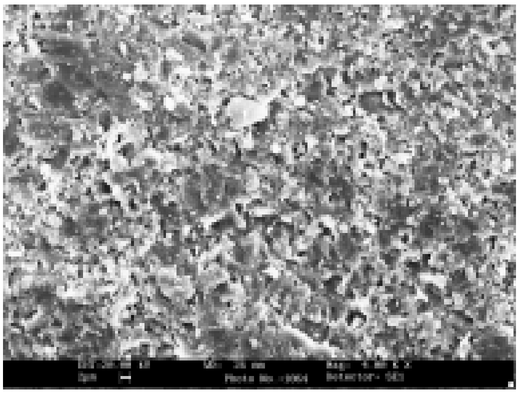
4.4 Breakage of Fibres

Typical front and rear side damage of the ceramic tile restrained by 8 layers of dyneema and twaron are shown in Fig. 12. From the photographs, it is

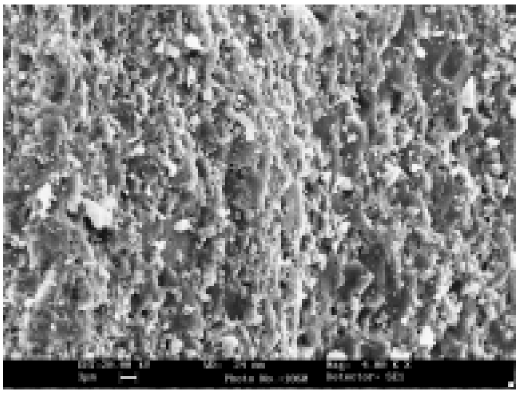
Table 3. Fragment size distribution of ceramic tile under different conditions of restraint

Name of the sample	Distribution of fragments (%)				
	> 700 µm	250-700 µm	150-250 µm	70-150 µm	< 70 µm
Bare tile	94	4	1.5	0.1	0.4
CD4	81	13	4	1.5	0.5
CD8	76	17	4	2	1.0
CT4	67	25	5.5	2	0.5
CT8	56	32	7.5	4	0.5

CD: Ceramic tile restrained with dyneema fa bric
CT: Ceramic tile restrained with twaron fabric



(a)



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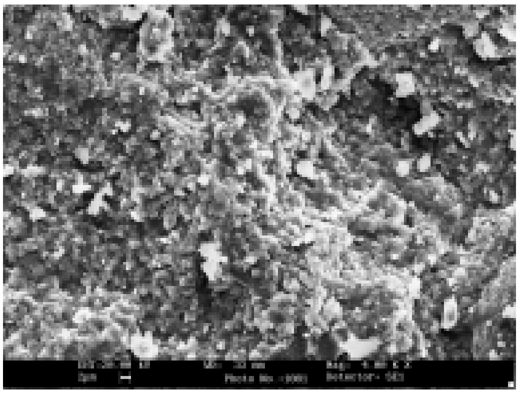
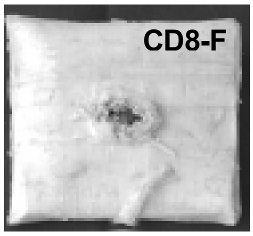


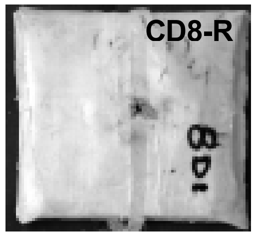
(c)

Figure 11. SEM images of various sizes of fragments from twaron restrained tiles: (a) 70 µm, (b) 150 µm, and (c) 700 µm.

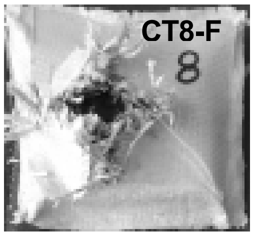
seen that the damage of the ceramic tile was contained within the restrained polymer layers. This shows that the comminuted ceramic continued to interact with the projectile during the penetration process of the projectile under well restrained condition, thereby, increasing the overall energy absorption by the configuration. For the projectile to advance, it is required that the



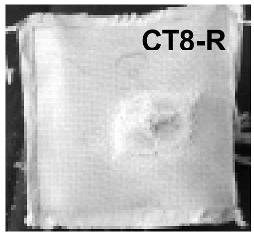
(a1)



(b1)



(a2)



(b2)

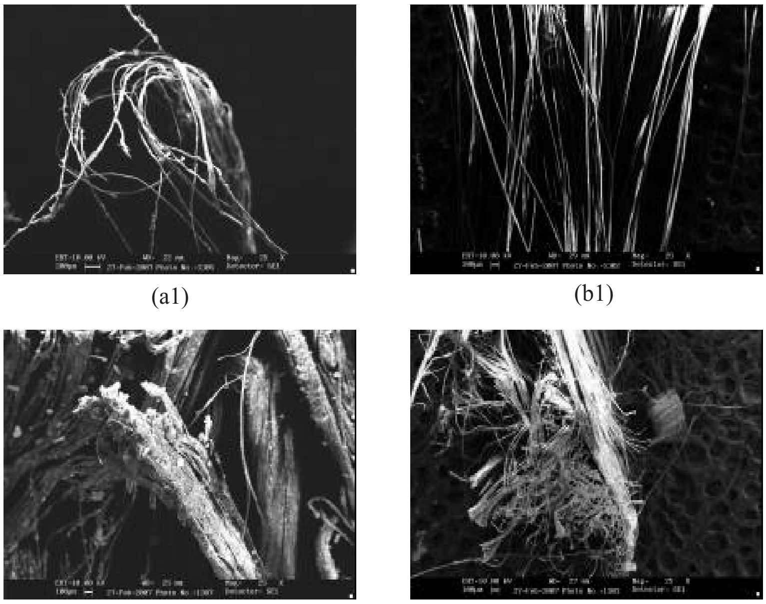
Figure 12. Photographs of (a) front and (b) rear damage of the ceramic tile restrained with 8 layers of: (1) dyneema and (2) twaron.

fine ceramic fragments in front of the penetrator move away from its path. Restraining the ceramic with polymer delays the above process and indirectly helps in generating more amount of comminuted ceramic that continues its interaction with the projectile.

On a closer examination of the front damage, it is seen that in the case of dyneema restraint, the fibre of the inner layers were found to be stretched but the strands of the fabric were intact. In the case of twaron restraint, the fibre were found to be broken in brittle nature and most of the strands were found disintegrated. The front layers opened up at the tip. SEM images of fibre from both the samples were studied. Figure 13 shows SEM images of the virgin fibre and fibre after impact collected from the impact point for both the varieties. These images suggest that the fibre failed after undergoing stretching and breakage while providing resistance to projectile as well as restraint to the ceramic tile during the process of penetration, thereby increasing the energy absorption of the configuration.

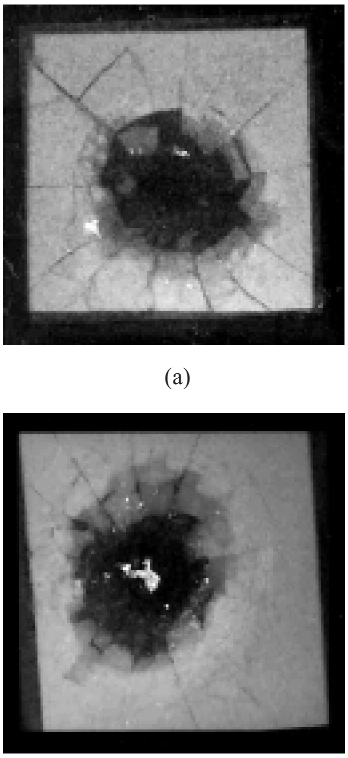
4.5 Radiography of the Ceramic Tiles

To study the damage in the restrained tile, the panels were radiographed. Figure 14 shows typical damage in ceramic confined by dyneema and twaron. Radial and circumferential macro-cracks are observed in both the cases.



(a1) (b1) (a2) (b2)

Figure 13. SEM images of fibres of: (a) dyneema and (b) twaron, taken from: (1) virgin material and (2) point of impact.



(a) (b)

Figure 14. Radiographs of damage in the ceramic tile restrained with 8 layers of: (a) dyneema and (b) twaron.

5. CONCLUSIONS

From the results of the above studies performed on the alumina samples impacted under restrained conditions, it is seen that there is a significant improvement in energy absorption of the ceramic tiles with the increase in number of confining layers. This is possibly due to the good confinement effect produced in ceramic tile, which results in comminuted ceramic participating in the projectile erosion and fracturing process for a longer duration. It is also supported by the reduction in residual mass of the projectile. It was also confirmed that as the confinement increases, the amount of finer fragmentation also increased. The more amount of finer fragmentation leads to generation of higher amount of surface area which ultimately absorbs more amount of energy. Fibre were seen to be stretching and fibre pullout was evident before failure of the fibre. In the case of twaron fibre, splitting of fibre bundles is also observed in addition, which helps in increasing the amount of energy.

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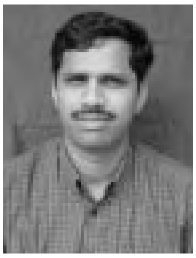
Contributors



Mr P. Rama Subba Reddy obtained his MSc (Polymer Sci) in 1998. Presently, he is working as Scientist C at DMRL, Hyderabad. He has more than nine years experience in various areas like surface coatings and protective coatings for automobile vehicles, radiation grafting, radiation polymerisation for the development of membranes and flame retardant fabrics, armour composites and their evaluation for ballistic applications. He has published six papers in international journals and conferences. He received the *Best Paper Award* during National Science Day 2005.

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