Numerical simulation of armor capability of Al₂O₃ and SiC armor tiles

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Abstract. Alumina and Silicon Carbide armor plates have been tested numerically against 7.62x51 (mm x mm) armor piercing (AP) projectiles. A 2-D problem with axial symmetry has been designed and the simulations were carried out using commercial software ANSYS AUTODYN. Experiments were modeled for Alumina (99.5%), Alumina (99.7%) and SiC with a range of tile thicknesses (5, 10, 15 and 20 mm). The projectile was chosen as 7.62 x 51AP bullet (initial velocity 810 m/sec) with two different core materials Steel 4340 and WC, however, casing material was copper for both cores. SiC showed better defense against AP bullet as compared to Al₂O₃. The residual velocity and momentum of the bullet were found to decrease with increasing tile thickness. SiC tiles with thickness 15mm and 20 mm successfully sustained penetration against steel 4340 and WC core bullets, respectively. However none of the Alumina targets succeeded in stopping the bullet.

1. Introduction
Protection of soldiers had been under focus since ancient times. With the modernization of arms, demand for rise in protection levels against potential threats has also been increasing. For designing of armor vest various parameters are taken into account i.e. threat level, durability, weight and cost etc. Ceramic armor’s are preferred over metals mainly for their low weight and increased durability. To design armor, hit and trial procedure is not viable for being costly and labor intensive.

Hazell et al. studied the penetration and failure mechanism of Silicon carbide tiles for 7.62AP projectiles using hydrocode Autodyne-2D. Critical tile area for optimized performance of square SiC tile has been worked out as 70 mm x 70 mm. M. V. Silva et al. studied mechanical properties of different Al₂O₃ compositions (92, 96 and 99 %). Al₂O₃ (92 % and 99 %) showed higher Vickers hardness and bend strength as compared to Al₂O₃ 96%. However, all three compositions did not allow penetration against AP-projectile (865 m/s). Hosein Kia et al. presented a comparison of theoretical and numerical results for effect of projectile density on its penetration capability into alumina armor. Ballistic limit velocity (BLV) of the alumina armor was calculated using LS-Dyna software. Results showed that increase in projectile density decreases BLV. Chetan Swaroop studied the use of Smooth particle hydrodynamics (SPH) solver of Autodyne-2D to simulate the performance of Al₂O₃ (99.7%) by Lead Round Nose projectile (LRN). The main result was an empirical relation between impact velocity and corresponding residual velocity for 6 mm thick ceramic plate (Al₂O₃-99.7%) with linear fit. R. Azaraftza et al. studied the impact behaviour of Alumina/Nano-SiC ceramic composite using both computational and experimental techniques.
Composites with 10% SiC doped Alumina showed improved ballistic behavior as well as low density as compared to pure Alumina. Z. Fawaz et al. [6] simulated the energy losses and stress distributions in ceramic-composite armor when subjected to normal and oblique 7.62 AP projectiles. Inter laminar stresses at the ceramic composite interface were found smaller for oblique impacts as compared to the normal impacts. Projectile erosion for oblique impacts was however greater than those for normal impacts. Daniel Bürger et al. [7] Simulations in ABAQUS were carried out for testing ceramic/fiber reinforced composite armors against 7.62 x 51 AP projectile impact. Results predicted a partial penetration at target speed 675 m/s and complete penetration at 765 m/s.

In the present work, AUTODYN-2D is used to evaluate and compare the impact resistance capabilities of three different ceramic materials against armor piercing bullets of two different types. Impact bearing capability of four different thicknesses of Alumina (99.7%), Alumina (99.5%) and Silicon carbide plates was simulated against armor piercing projectiles with steel4340 and tungsten carbide cores.

2. Materials and methods

2.1 Autodyn-2D

Autodyn-2D is a module of commercial software ANSYS and is used for the non-linear analysis of high velocity impact problems, high and low distortion problems and for projectile and target interaction related problems [8]. The 2D model was designed in the Preprocessor (ANSYS DESIGN MODELER). Geometry was then imported to AUTODYN-2D (Solver & Post Processor) for further analysis. General setup of the model is shown in Figure 1.

![Figure 1. General setup of AP-bullet projectile and ceramic target](image)

2.2 Projectile

In the present work, 7.62x51 mm NATO armor piercing (AP) bullet was used as projectile. The total length of the projectile is 51 mm and the maximum diameter is 7.61 mm. Projectile was integrated of hard material inner core (WC and Steel4340) and metal (copper) outer jacket/casing. Two different core materials, WC and Steel 4340 were used in simulation experiments. Thickness of the copper casing was taken 1 mm and diameter of the core was fixed as 6.61 mm, as shown in Figure 2. The initial velocity of 810m/sec was assigned to the bullet. The material model and properties for above mentioned materials were taken from AUTODYN Materials Library.

2.3 Target

Three different materials; \( \text{Al}_2\text{O}_3 \) (99.7%), \( \text{Al}_2\text{O}_3 \) (99.5%) and SiC were used as targets. Bullet penetration simulations were carried out for four different thicknesses; 5, 10, 15 and 20 mm of each
of the three ceramic materials. Fixed boundary condition (or Support) was applied to the upper edge of the target. Height of each target was 30 mm as show in Figure 2.

![Figure 2. Mesh design for the bullet and the target](image)

### 2.4 Meshing
In the AUTODYN-2D, quadrilateral meshing was introduced to both the bullet and the ceramic target. While size of quadrilateral element was fixed as 0.1 mm. The number of elements and nodes for the casing and the target are given as

|               | Bullet | Target |
|---------------|--------|--------|
| **No. of Elements** |        |        |
| Casing        | 5886   | 16457  |
| Core          | 16457  | 1962   |
| 5mm           | 1962   | 2976   |
| 10mm          | 2976   | 3362   |
| 15mm          | 3362   | 3700   |
| 20mm          | 3700   |        |
| **No. of Nodes** |        |        |
| Casing        | 6449   | 16990  |
| Core          | 16990  | 2090   |
| 5mm           | 2090   | 2852   |
| 10mm          | 2852   | 3240   |
| 15mm          | 3240   | 3577   |
| 20mm          | 3577   |        |
| **Skewness**  | 0.843  | 0.843  |

### 2.5 Models used for materials
The material models and properties for the Steel 4340, Copper, Alumina 99.5, Alumina 99.7 and Silicon Carbide were taken from AUTODYN materials library ENREF 8. The Johnson-Cook model was used for failure analysis of Steel4340 core and Copper jacket. At non zero strain rate the yield stress ($\sigma$) depends on the equivalent plastic strain ($\varepsilon^{pl}$), reference strain rate ($\dot{\varepsilon}_0$) and softening temperature ($\dot{\theta}^m$) given by [8]

$$\sigma = \left(A + B(\varepsilon^{pl})^n\right) \left[1 + C \ln\left(\varepsilon^{pl}/\dot{\varepsilon}_0\right)\right] \left(1 - \dot{\theta}^m\right)$$  \hspace{1cm} (1)

Where $A$, $B$, $C$, $n$ and $m$ are material parameters.

$$\varepsilon^{pl} = \left[d_1 + d_2 \exp\left(\frac{\dot{\varepsilon}}{q}\right)\right] \left[1 + d_3 \ln\left(\varepsilon^{pl}/\dot{\varepsilon}_0\right)\right] \left(1 + d_4 \dot{\theta}\right)$$  \hspace{1cm} (2)

Where $q$, $p$ and $d_1$ – $d_5$ are Mises stress, mean stress and failure parameters, respectively. Values of $d_1$ – $d_5$ have been mentioned in Table 2.

|               | $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ |
|---------------|-------|-------|-------|-------|-------|
| $D_1$         | 0.05  | 3.44  | 2.12  | 0.002 | 0.61  |

Table 2. Failure parameters of Johnson-Cook Model for Steel 4340
The failure model for copper considers failure strain of the value 0.4 and erosion geometric instantaneous strain is 2[8].

3. Results and discussion

3.1 Simulation of penetration

Figure 3 shows the penetration of steel 4340 core bullet in three different ceramic materials with varying thickness. It can be observed that the bullet penetrates almost un-hurt through 5 mm thick Alumina (99.5 and 99.7%), however its cone face in blunted case of SiC (5 mm) tile. Reduction in velocity and momentum of the bullet against all three tiles is almost negligible as evident from Fig. 5 and Fig. 7, respectively.

For 10 mm tile thickness, Alumina 99.5% is found to show better resistance as compared to Alumina 99.7%. For SiC 10 mm, the bullet (core steel 4340) has penetrated successfully but it is fragmented. Percentage reduction in velocity and momentum are less than 10, however SiC can be seen on the upper edge in Fig. 5 and Fig. 7.

![Figure 3. Penetration of 7.62 AP (Core: Steel4340) bullet in Alumina and SiC targets of thicknesses](image-url)
For tile thickness 15mm, the bullet is found to penetrate the Alumina 99.7% target by scattering the tile into fragments. In case of Alumina 99.5% a single major crack can be observed in the tile and bullet is fragmented. SiC (15mm) tile has been able to survive the attack by blocking the bullet while developing few major cracks in itself. Reduction in velocity and momentum are almost identical for both Alumina-99.5% and Alumina-99.7%, which is around 20% of the initial. However, SiC has successfully absorbed the bullet energy while reducing the velocity and momentum of the bullet to zero.

By further increasing the tile thickness to 20 mm, it has been observed that Alumina 99.7% has failed to survive the attack of steel 4340 bullet, however Alumina 99.5% has been able to completely scatter the bullet into tiny fragments.

Figure 4 shows the penetration of WC core bullet in three different ceramic materials tiles with varying thickness. Complete penetration can be seen in all compositions with thickness 5mm, however minor damage to the copper casing is observed.

For 10 mm tile thickness, Alumina 99.5% imparted more damage to the bullet as compared to Alumina 99.7%. For SiC 10 mm tile, considerable damage can be observed as the bullet is divided into tiny fragments while penetrating through the tile.

In case of 15 mm thick tile, the WC core bullet has penetrated through all three materials. Alumina 99.7% presented the least resistance by only blunt the cone of the bullet. Alumina 99.5% posed comparatively better resistance as we see fragmented bullet however the tile also developed major cracks. Unlike Steel 4340 core bullet, the WC core bullet succeeded in completely penetrating the SiC 15mm tile however tearing itself into fragments.

For the 20mm tile, both Alumina 99.7 % and 99.5 % failed to survive the attack of the WC core bullet, however in this case as well SiC has been able to block the penetrator while developing a few major cracks in itself.

| Thickness | Alumina (99.5%) | Alumina (99.7%) | SiC |
|-----------|-----------------|----------------|-----|
| 5mm       | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
| 10mm      | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |

Figure 4. Continue
3.2 *Reduction in bullet velocity*

Figure 5 and Figure 7 show residual velocity and residual momentum of the Steel4340 core bullet after striking the target. Results of residual velocity and momentum against Alumina (99.5% and 99.7%) targets showed almost same trend for the whole thickness range. In case of SiC tiles (5mm and 10mm) the residual velocity and momentum was comparable to that of Alumina (99.5% and 99.7%). However, 15mm and 20mm SiC tiles reduced the speed of the Steel4340 to dead level.

Figure 5. Reduction in velocity of Steel4340 core bullet against different thicknesses of alumina and SiC

Figure 6: Reduction in velocity of WC core bullet against different thicknesses of alumina and SiC

Figure 6 and Figure 8 show residual velocity and residual momentum of the WC core bullet after striking Alumina and SiC targets. Results of residual velocity and momentum against Alumina (99.5% and 99.7%) targets showed almost same trend for the whole thickness range. In case of SiC tiles (5mm and 10mm) the residual velocity and momentum were comparable to that of Alumina (99.5% and 99.7%). However, 20mm SiC tiles reduced the speed of the Steel4340 core to dead level.
Figure 7. Reduction in momentum of Steel 4340 core bullet against different thicknesses of alumina and SiC

Figure 8. Reduction in momentum of WC core bullet against different thicknesses of alumina and SiC

Figure 9. Curve fitting on residual velocity of sheet 4340 bullet against different SiC tile thicknesses

The relationship between residual velocity of steel 4340 bullet and SiC tile thickness is derived by curve fitting as shown in Figure 9.

\[
V_r = V_0 + A e^{-\frac{t}{\lambda_1}} + B e^{-\frac{t}{\lambda_2}}
\]

Where \(V_0\) is the initial velocity of the bullet, while \(A\) (=-1.028E-05), \(B\) (-28.02) are amplitudes, while \(\lambda_1\) (-0.8621) and \(\lambda_2\) (-6.027) are decay constants or fitting constants.

4. Conclusions
Alumina and Silicon Carbide armor plates were subjected to high velocity (810 m/s) impact of 7.62x51 mm² AP projectiles. AUTODYN results show SiC plates is a better option for armor applications as compared to Alumina. SiC(15mm) stopped penetration effectively against Steel4340 core bullet, however, 20mm tile was found sufficient to stop WC core bullet. All thicknesses up to 20 mm failed to stop penetration against both steel 4340 and WC core bullets.

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