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Influence of Geometry and Hardness of the Backing Plate on Ballistic Performance of Bi-Layer Ceramic Armor

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Abstract

The high hardness and strength of technical ceramics is exploited to design ballistic armors and their low toughness, brittleness is overcome by joining them with a metallic or long fiber reinforced composite backing plate. The thickness of backing plate (BP) on the ballistic performance SiC ceramic armor is studied through finite element simulations based on AUTODYN®. In this work, depth of penetration (DOP) from experimental measurements is compared with simulations using explicit software AUTODYN® for 3D modelling. The ballistic performance of three layer armor (cover plate (CP), ceramic tile and backing plate (BP)) under normal and oblique (NATO 60°) for long rod projectile (LRP) with a conical tip is investigated. The LRP and CP have been modelled using smooth particle hydrodynamic (SPH) particles and rest of the component is modelled using lagrangian processor. The Johnson-Cook and Johnson-Holmquist (JH-2) constitutive models are used for metal and ceramic materials, respectively. It is found that thicker BP enhances SiC armor via supporting longer period and prevent any premature failure at the rear surface of ceramic. It is also noticed that high hardness (low ductile) BP improves the ballistic performance of ceramic armor through offsetting tension of ceramic.

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Keywords: *Ceramic armor, interface defeat, dwelling, confinement*

1. Introduction

Technical ceramics such as alumina, silicon carbide, boron carbide are commonly used as armor because of their high specific hardness and compressive. However, being brittle in nature ceramic suffers from disintegration under impact loading. Inclusion of suitable support system can mitigate the damage intensity on the ceramic surface, thereby improving the performance of armor. The ballistic performance of ceramic armor depends on geometrical and materials properties, interface bonding properties, angle of attack. The enhancement in the performance of

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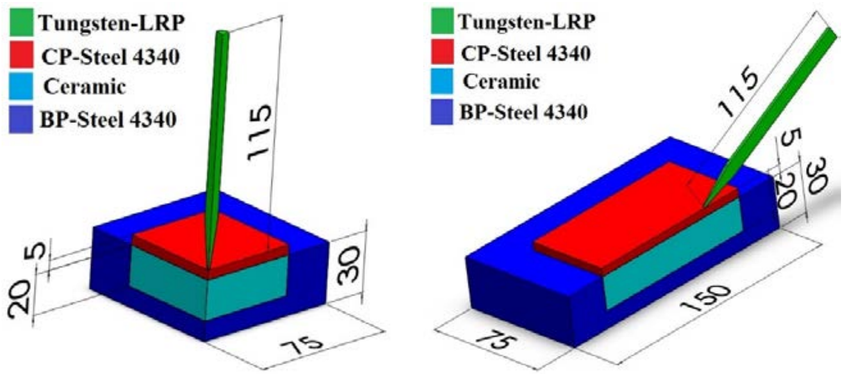
ceramic armor has been studied by many researchers [1-7] and noted that keeping the damaged ceramic in place via confinement or pre-stressing or through buffer plate enhances the ballistic performance of armor. This strengthen the ceramic armor and forces high velocity projectile to flow radially at the interface with or without any significant penetration, a phenomenon called dwell or interface defeat. In the literature, dwell is usually referred to radial flow of the projectile on the surface of the target for some time (dwell time) followed by penetration into the ceramic while if no penetration occurs the phenomenon is termed as interface defeat. Dwell or interface defeat are important mechanisms during which the kinetic energy of the projectile is considerably reduced and therefore survivability of the ceramic target is increased.

In this paper the effect of BP thickness and hardness on ballistic performance of SiC under long rod projectile (LRP) normal and oblique impact is investigated using AUTODYN® hydrocode simulations. Material models used in simulations are validated against depth of penetration (DOP) experimental results from the literature.

2. Three Dimensional (3D) Simulations

In this section, carried out numerical work based on AUTODYN® 3D are presented for normal and oblique (NATO 60°) under long rod projectile (LRP) impact. The LRP used in all the normal and oblique impact simulation is conical-end tungsten projectile of 8.3 mm in diameter and 115 mm length with a cone angle of 60°. The SiC tile of 20 mm thick 100 mm x 100 mm is encased in steel confinement with a cover plate of 5 mm thickness. All the interfaces between to reduce computation time, by exploiting symmetry with respect to geometry and loading conditions, a quarter model for normal and half model for oblique (due to asymmetric penetration) impact are discretized, as shown in Figure 1. Projectile and cover plate are discretized using smooth particle hydrodynamic domain (SPH) of particle size 0.5 mm

The CP planar dimension was considered 50 mm× 50 mm to save computational cost and it was fixed in its periphery. The element size for SiC and BP, in its central area 24 mm is 0.6 mm. Clamped boundary condition was applied on the periphery of the confinement. LRP impact velocity in this section is fixed at 1244 m/s. This mesh size and geometries are used for all the other normal impact simulations for the parametric study in the investigations.



(a) (b)

Figure 1: Schematic of SiC-steel armor with cover plate (a) quarter model for normal impact (b) half model for oblique impact. All geometrical dimensions are in mm.

Three dimensional (3D) half model for the oblique impact onto SiC-steel 4340 target was built in AUTODYN® to save the computational cost. The LRP and CP were modeled using SPH particles of 0.55 mm particle size. The LRP of 60 ° obliquity impacts the target at an off-centered point, almost 36 mm from the center reference point. The steel 4340 target in which the SiC is embedded is considered as cube. The "SiC-steel 4340 target" was discretized using Lagrangian elements. The element size in the SiC cube central region, (-45mm<z<30mm, 0mm<x<20mm), through the thickness, i.e. 0 to 20 mm in y direction, were 0.6 mm and the element size in the remaining region toward the periphery of the SiC is gradually increased. The steel 4340 target below the SiC target through the thickness and in x and z direction of -30mm<z<45mm and 0mm<x<20mm is discretized using 0.6 mm element size.

The steel 4340 in other regions is gradually increased toward the periphery of the target. Erosion strain of 2 was used for steel 4340 and SiC material. LRP impact velocity in this section is fixed at 1300 m/s. This mesh size and geometries are used for all the other oblique impact simulations. Material properties of SiC and tungsten alloy are listed in Table 1.

Table 1 Properties of SiC and Tungsten LRP.

Component	Material	Density (g/cm^3)	Young's modulus (GPa)	Tensile strength (MPa)	Compressive strength (GPa)	Hardness	Reference
LRP	Tungsten	17.6	325	920	NA	HBW 277	[8]
Ceramic	SiC-F	3.23	420	400	>2.50	VH 26 (GPa)	[9]

2.1. Validation of Material Model

DOP experimental setups and measurements are modelled as quarter model in AUTODYN® 3D. The Johnson-Cook (JC) material model parameters of steel 4340 can be found in [12], and tungsten alloy in [10, 11]. The SiC is modelled with Johnson-Holmquist (JH-2) constitutive model and their parameters are listed in [13-15]. The simulations results are validated through experimental DOP measurements and are plotted in Figure 2. The DOP is measured as the penetration depth caused by the LRP in the witness or supporting block of steel 4340. At the low velocity 940 m/s, the LRP dwelled at the surface of SiC and there was no evident penetration observed. However, as the velocity increases from 940 m/s to 949 m/s, a significant increment in DOP of 11 mm was noticed. This can be attributed to the sensitiveness of dwell to transition velocities.

At the higher velocities ranging from 1200 m/s the trend was stable in experiments and similar behaviour was shown by the performed simulations. At the lower velocities the error in matching DOP was above the 40% and at the transition velocities (high velocities), the error was reduced below 30% and even in some cases it was below to 5%. The variation in the results of simulations could be due to tie join between SiC and backing support (perfect bonding) in simulations while in the experiments adhesive (~0.5 mm) is used.

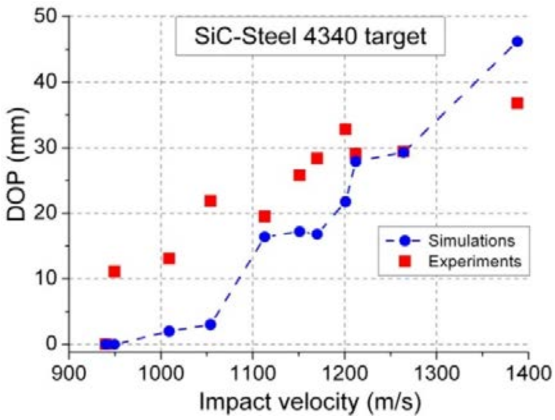
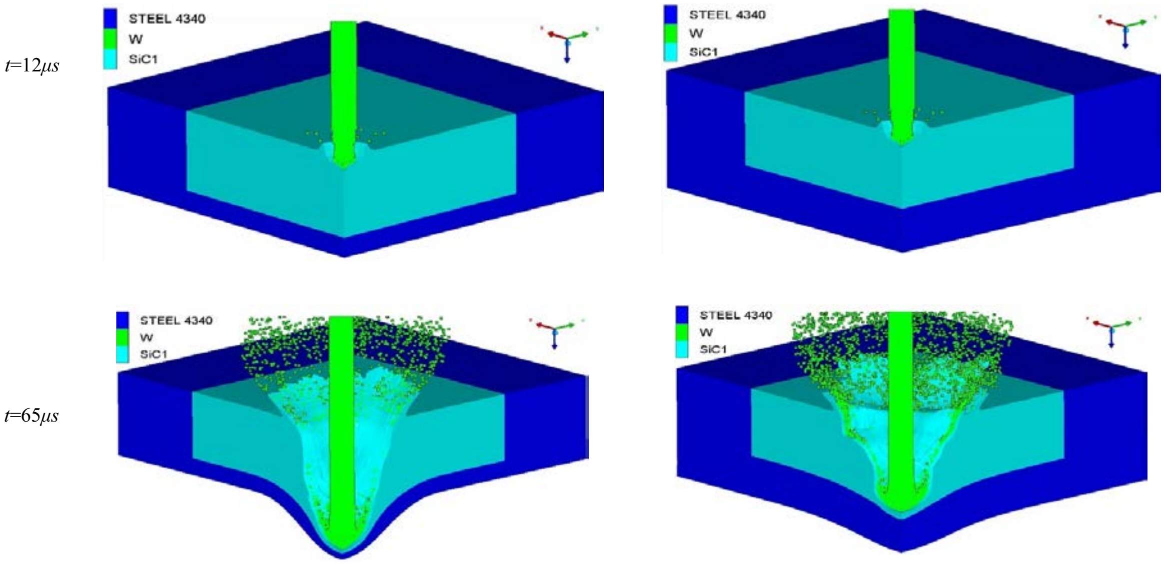


Figure 2: Comparison between 3D simulations and experimental DOP results on "SiC-steel 4340 target" under different impact velocities.

2.2. Effect of Backing Plate thickness on Ballistic Performance

Inclusion of BP in to ceramic armor improves the ballistic performance by supporting ceramic and preventing the tensile failure at rear side the ceramic.

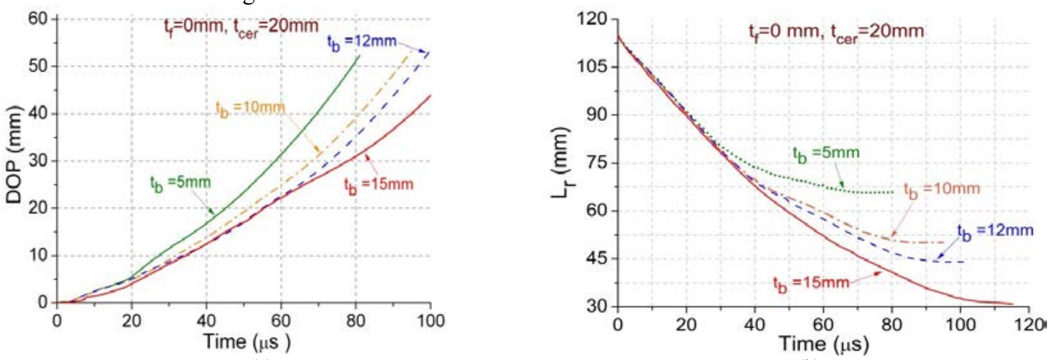
Normal Impact: For the parametric study, targets with and without cover plates (CP), different backing plates (BP), t_b, and ceramic tiles, t_{cer}, thicknesses are used in normal impact simulations. Figure 3 shows projectile penetration at different times under normal impact with 1244 m/s velocity onto two targets of fixed SiC tile thickness, t_{cer}=20 mm, zero front CP thickness, t_f = 0 mm and one with BP thickness, t_b=5 mm and the other with BP thickness, t_b=12 mm. It can be seen that the former shows larger DOP compared to the latter through the course of penetration. The reason is that thicker backing plate supports the SiC tile for longer time which results in larger deformation and bending of SiC rear side, thereby rendering SiC tile prematurely failed in tension. SiC tile of thinner backing support can comparatively erode LRP and decrease its velocity with smaller rate throughout the LRP penetration, hence larger DOP and LRP residual length, L_r.



(a) t_b=5 mm (b) t_b=12 mm

Figure 3 Projectile penetration at different times for normal impact of LRP of 1244 m/s initial velocity onto armor of fixed SiC tile thickness, t_{cer}=20 mm, CP thickness, t_f = 0 mm and (a) BP thickness, t_b=5 mm and (b) BP thickness, t_b=12 mm.

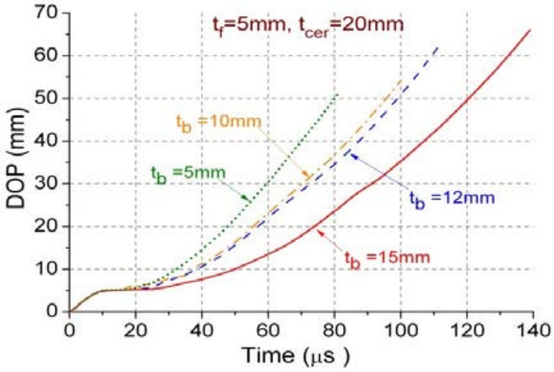
Thicker and well bonded (adhesive) BP enhances the stiffness of target and support ceramic target in eroding the projectile. This can be seen in Figure 4(a) and (b), respectively, showing DOP and L_r in LRP impact onto targets of fixed SiC tile thickness, t_{cer}=20 mm, CP thickness, t_f = 0 mm and different BP thicknesses, t_b. It can be seen that increases in BP thickness strengthens the ceramic armor.



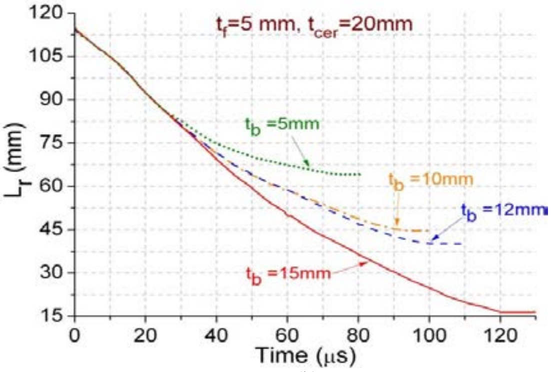
(a) (b)

Figure 4: Temporal variation of (a) DOP and (b) LRP residual length, L_r, for normal impact of LRP of 1244 m/s initial velocity onto armors of fixed SiC tile thickness, t_{cer} =20 mm, zero front CP thickness, t_f = 0 mm and different BP thickness, t_b.

In different segment the influence of BP on ceramic armor with CP is explored and obtained results are plotted in Figure 5 (a) and (b). The behaviour is similar; the thicker BP supports longer time and mitigates the possible tensile failure at the rear side of the ceramic. It is found that without CP in front of SiC (thickness of 20 mm), is not enough to achieve interface defeat.



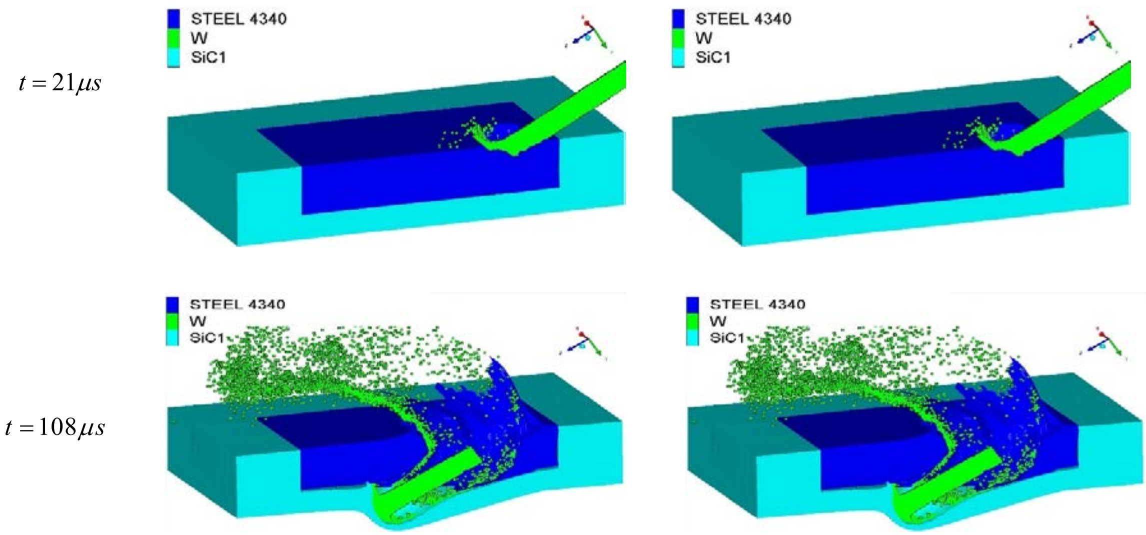
(a)



(b)

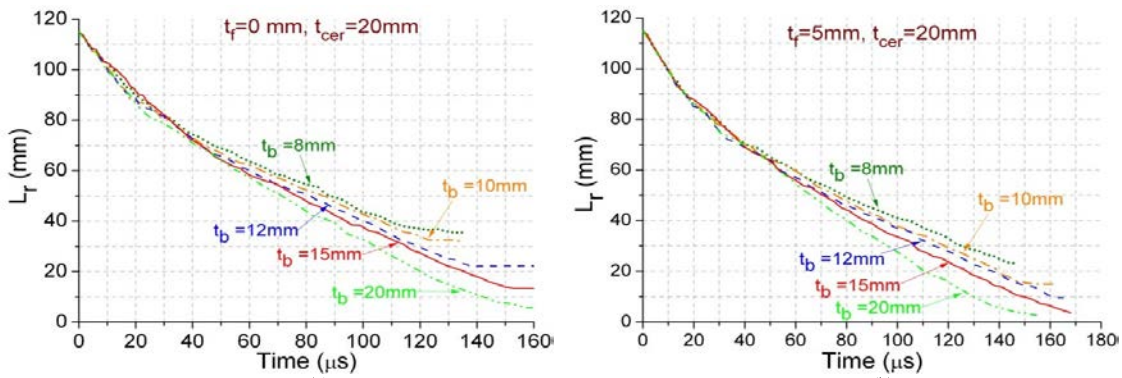
Figure 5 Temporal variation of (a) DOP and (b) LRP residual length, L_r, for normal impact of LRP of 1244 m/s initial velocity onto armors of fixed SiC tile thickness, t_{cer}= 20 mm, front CP thickness, t_f = 5 mm and different BP thickness, t_b.

Oblique Impact: The ballistic performance of armor module under oblique impact is only measured though L_r since it difficult to collect data for DOP due to asymmetrical penetration. Figure 6 shows projectile penetration at different times in oblique impact at 1300 m/s initial velocity onto two targets of fixed SiC tile thickness, t_{ce}r=20 mm, CP thickness, t_f = 0 mm and one with BP thickness, t_b=10 mm and the other with BP thickness, t_b=15 mm. Figure 7 (a) and (b) shows the L_r for with and without CP armor module. It can be seen that thicker BP support ceramic for longer time and helps in reducing penetration efficiency of LRP by reducing it length.



(a) t_b=10 mm (b) t_b=15 mm

Figure 6 Projectile penetration at different times for oblique impact of LRP of 1300 m/s initial velocity onto armor of fixed SiC tile thickness, t_{cer}=20 mm, zero front CP thickness, t_f = 0 mm and (a) BP thickness, t_b=10 mm and (b) BP thickness, t_b=15 mm.



(a) (b)

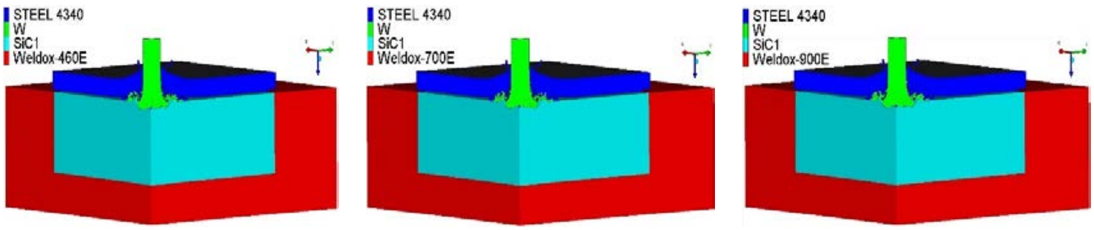
Figure 7: Temporal variation of LRP residual length, Lr, for oblique impact of LRP of 1300 m/s initial velocity onto armors of different BP thickness, tb, fixed SiC tile thickness, tcer=20 mm and (a) fixed CP thickness, tf=0 mm and (b) and fixed front CP thickness, tf=5 mm.

2.3. Effect of Backing Plate hardness on Ballistic Performance

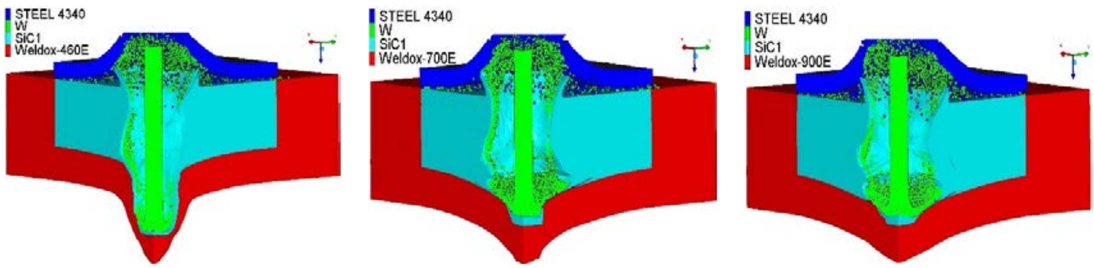
The material properties and response of BP play significant role in the ballistic performance of armor and explored in this section through using three different hardness BP namely: Weldox 460E, Weldox 700E and Weldox 900E. The failure mode of hardened steel changes as the hardness increases and influences the armor performance. The JC material parameters of Weldox steel for different hardness are reported by Dey. et.al[16].

Normal Impact: Figure 8 shows material location at different times for normal impact of LRP of 1244 m/s initial velocity onto armor of fixed SiC tile thickness, t_{cer}=20 mm, front steel 4340 (30 HRC) CP thickness, t_f=5 mm and BP thickness, t_b=10 mm made of three materials, namely Weldox 460E, Weldox 700E and Weldox 900E. This had been depicted in Figure 9(a) and (b) showing that with increase in hardness of BP, rate of penetration onto the ceramic decreases and rate of erosion of the LRP increases. It is evident in Figure 8 that ductile behaviour (plastic deformation of Weldox 460E to absorb the residual LRP energy) of BP allows SiC (being brittle materials in nature possesses poor performance under bending stresses) to expand outward which led to fail SiC early. On the other hand, stronger (high hardness Weldox 900E) BP doesn't display plastic deformation and resulting in better performance. However, the modes of failure (behaviour to absorb residual energy) changes as the hardness increases, the ductile BP shows more elongation while the hardened steel shows brittle (plug) response. Hence with increase in hardness of BP, deformation of the BP is reduced and therefore, the SiC has stronger backing support through the penetration of LRP and it can erode the LRP with ease.

t=25*μs*

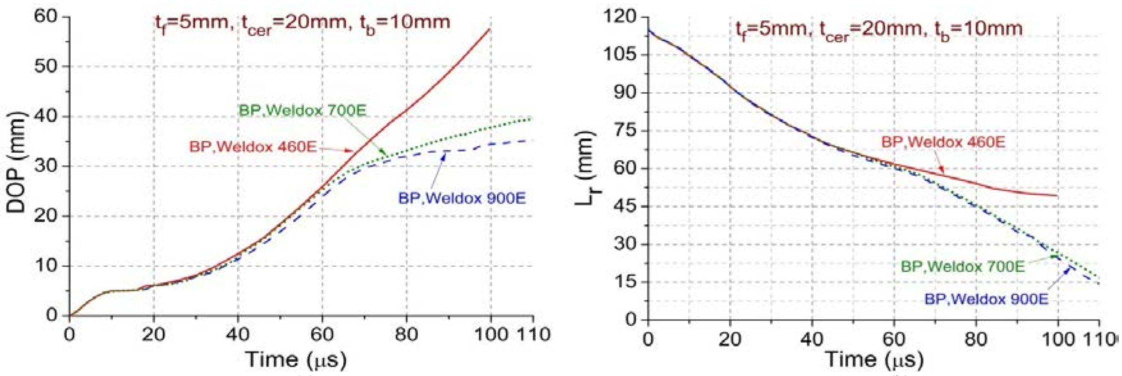


t=89*μs*



(a) BP,Weldox 460E (b) BP,Weldox 700E (c) BP,Weldox 900E

Figure 8 Projectile penetration at different times for normal impact of LRP of 1244 m/s initial velocity onto armor of fixed SiC tile thickness, t_{cer}=20 mm, front steel 4340 (30 HRC) CP thickness, t_f=5 mm and BP thickness, t_b=10 mm made of (a) Weldox 460E, (b) Weldox 700E and (c) Weldox 900E.



(a) (b)

Figure 9 Temporal variation of (a) DOP and (b) LRP residual length, L_r, for normal impact of LRP of 1244 m/s initial velocity onto armors of fixed SiC tile thickness, t_{cer} =20 mm, front CP thickness, t_f=5 mm and BP thickness, t_b=10 mm made of Weldox 460E, Weldox 700E and Weldox 900E.

3. Summary and Conclusion

In this work, effect of backing plate (BP) thickness and hardness with and without cover plate (CP) on a SiC armor module are explored via extensive numerical simulation using AUTODYN® commercial software. The major findings are as follows:

1. It was found that with increase of BP thickness, depth of penetration (DOP) as well residual length, Lr, of the long rod projectile, decrease: thicker BP support longer time ceramic and prevent the bending at the rear side of ceramic, resulting in improvement in the ballistic performance of the armor module.
2. Inclusion of thicker BP offset the tensile stresses at the rear surface of SiC tile and prevent from premature failure. It also keeps damaged ceramic in place and provides resistance to LRP.
3. It was shown that both DOP and Lr decrease as BP hardness increases. High hardness materials show less bending and continue to support rear side of ceramic tile without any sign of ductility. The high hardness material absorbs the energy via crack (brittle in nature) and help in eroding projectile with higher erosion rate.

4. The hardness of BP decreases mitigates the damage on SiC tile efficiently up to certain level and the modes of failure changes from shear to plugging. It is also concluded that high hardness is not the lone reason to have interface defeat.
5. Cover plate and BP are two important components in the ceramic armor design to have an optimal (light weight) design and better functionality (advanced dwelling and interface defeat) against LRP.

Acknowledgements

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