Defence Science Journal, Vol. 52, No. 4, October 2002, pp. 429-438

Effect of Flyer Plate Velocity and Rate of Crater Expansion on Performance of Explosive Reactive Armour

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ABSTRACT

The reduction in the penetration power of the jet due to its interaction with an obliquely moving plate of explosive reactive armour (ERA) sandwich has been studied. It has been assumed that the length of the jet, which gets disturbed due to its interaction with the edge of the hole made by the impact of the tip of the jet when the plate was stationary, does not contribute to penetration in the target. The jet length, which comes out of the hole undisturbed, penetrates the target. This length of the jet has been calculated considering the variation in plate velocity and rate of expansion of the crater in the plate with time. The time taken by the jet to shift its position from the centre to the wall of the hole has been determined for different velocities of the sandwich plate and varying expansion rates of the hole produced by the jet in the plate, corresponding to a constant velocity of the jet. This analysis has been used to obtain the length of undisturbed jet coming out of the hole and its penetration in the target. The present study establishes the effect of the plate velocity and rate of crater expansion on the performance of the ERA. It has been found that both these parameters affect the performance of the ERA, and the metal plates of lower density and higher strength make the ERA more effective.

Keywords: Explosive reactive armour, shaped charge jet, add-on armour, warheads, precision-shaped charge warhead, target penetration, flyer plate velocity, crater

NOMENCLATURE

t	Time axis
S_0	Stand-off distance between virtual origin and impact point of jet
Z_0	Stand-off distance between moving plate and target
dp	Thickness of metal plate
dx	Thickness of explosive
d_j	Diameter of jet
ρ_p	Density of plate material
ρ_t	Density of target material
ρ_x	Density of the explosive
ρ_j	Density of the jet
θ	Angle of impact of jet wrt plate normal
V_{j0}	Tip velocity of the jet
V_{j1}	Jet exit velocity through 1st place
V_{jx}	Exit velocity of the jet through explosive
V_{j2}	Exit velocity of the jet through 2nd plate
V_{jc}	Velocity of the jet interrupted by the moving plate

Revised 04 March 2002

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$t_0=S_0/V_{j0}$	Time of impact of jet tip on plate
U_s	Shock velocity in metal plate
U_{av}	Average penetration rate of the jet
R_j	Radius of the jet
R_{CM}	Maximum radius of the crater
R_t	Strength of the target
T_f	Time to reach final radius by the crater
P	Pressure of the detonation products
M	Mass per unit area of the plate
C	Mass per unit area of the explosive
V	Volume of the detonation products
X	Distance axis
u	Velocity of detonation products in contact with the plate
c	Velocity of the sound in detonation products
γ	Adiabatic exponent of detonation products
u_j	Particle velocity of detonation products at C-J plane
C_j	Sonic velocity of detonation products at C-J plane
D	Velocity of detonation of an explosive
L	Half the thickness of the explosive
U_f	Final value of flyer plate velocity
Y	Distance moved by the plate
R_C	Radius of the crater
R_S	Distance shifted by the jet
T	Time required by the plate to move a distance Y
T_c	Critical time when the jet shifts to crater wall
P_j	Jet penetration in the target.

1. INTRODUCTION

Explosive reactive armour[1] (ERA) is the most effective add-on armour to provide protection to main battle tanks[1] against precision-shaped charge warheads. It basically consists of an explosive layer sandwiched between two metal plates. When a shaped charge jet strikes and penetrates the sandwich obliquely, the explosive layer between the plates is initiated by the impact of the jet and the pressure of detonation products moves the plates across the jet. During this motion, both lower and upper plates of the ERA sandwich are penetrated and cut by the shaped charge jet. The edge of the fast moving metal plate and also high-density detonation products disturb the linearity and the uniformity of the jet, and consequently reduce its power to penetrate the target.

Many investigators have studied the parameters of the ERA, which affect its performance against a shaped charge jet. Yadav[2] has theoretically studied the interaction of an explosively accelerated metal plate with an ideal-shaped charge jet on the basis of effective jet length. Yadav[3], *et al.* have also calculated jet penetration in the target across an ERA sandwich. The analysis is based on the assumptions that the plates of the sandwich move with uniform velocity and the jet is consumed in cutting these plates. Recently, Held[4] has investigated the effect of delay in initiation of explosive on the performance of ERA. This paper presents the effect of plate velocity and rate of expansion of the crater in the sandwich plate on the performance of the ERA.

2. FORMULATION OF PROBLEM

Let a shaped charge jet be produced at virtual origin at time $t = 0$ at a stand-off distance S_0 from the point of impact A on an ERA sandwich as shown in Fig.1. The ERA sandwich consists of two metal plates, each of thickness dp and an explosive layer of thickness dx, and is positioned at a distance Z_0 from the target. The density of the target is ρ_T and that of the metal plates of the ERA sandwich is ρ_P. The shaped charge jet strikes the sandwich with an initial velocity V_{j0} obliquely at an angle θ with the normal to the top plate of the sandwich. The shaped charge jet penetrates and makes a time-dependent hole of diameter bigger than the diameter of the jet (d_j), in the top plate and strikes the explosive layer and initiates an instantaneous detonation. The pressure of detonation products accelerates the metal plates to a final velocity[5] U_f which is a function of charge-to-metal mass

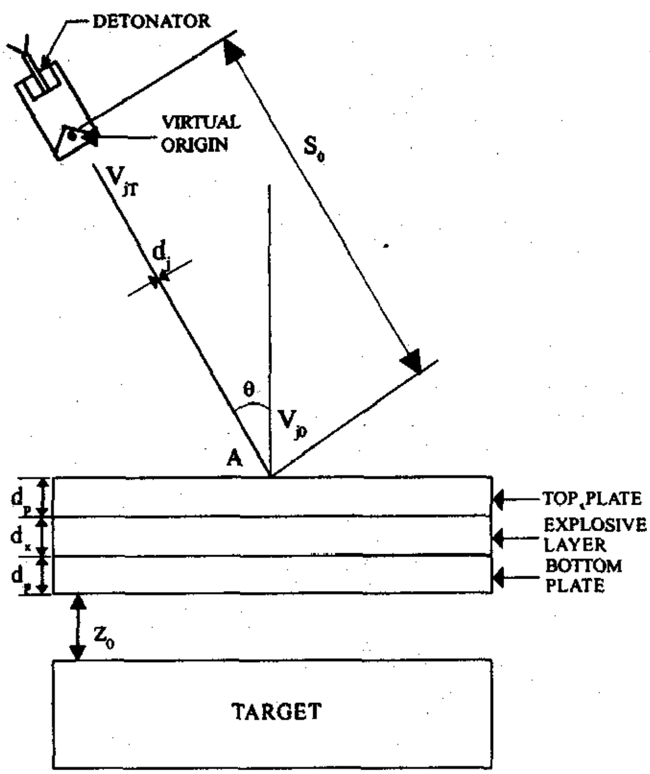

Figure 1. Impact of shaped charge jet on ERA sandwich at time, $t = t_0$.

ratio (C/M) of the sandwich. When the metal plates move obliquely in the direction of the jet, the position of the jet inside the hole shifts from the centre to the wall of the hole. After the jet has touched the wall, it interacts with the edge of the hole and gets disturbed. Thus, only a part of the complete jet length passes through the hole undisturbed. The problem at hand is to investigate the effect of the time-dependent plate velocity and the rate of crater expansion on the length of the undisturbed jet.

To simplify the theoretical analysis of this problem, the following basic assumptions have been made:

(a) Yield strengths of the target and sandwich materials are negligible as compared to the dynamic pressure generated by the impact of the jet. (In other words, the jet penetrates the target and the sandwich materials hydrodynamically)

(b) Initiation of detonation in the explosive layer, sandwiched between the metal plates, due to jet impact is instantaneous

(c) Shock and rarefaction wave velocities in the metal plates are comparable

(d) Metal plate under explosive loading moves as a rigid body

(e) Shaped charge jet remains continuous during its interaction with sandwich metal plates

(f) Jet impact on the sandwich is always oblique.

3. SOLUTION OF PROBLEM

The solution of the problem is sought by determining the instant of time when the shift in the jet is just enough to touch the wall of the expanding hole. If the jet is formed at virtual origin at time, $t = 0$, tip of the jet impacts the top plate at time, $t = t_0$ and, $t_0 = S_0/V_{j0}$. The jet, after penetrating the top plate, impinges upon the explosive layer. Assuming that the detonation is initiated in the explosive layer instantaneously, the amount of time t_1 elapsed in penetrating the top plate and the commencement of its motion can be approximated by the relation

$$t_1 = \frac{dp \sec\theta}{U_{av}} + \frac{2dp}{U_s} \tag{1}$$

where U_{av} is the average rate of penetration and U_s is the shock velocity in the plate. The term $2dp/U_s$ in Eqn (1) represents the total time of shock and rarefaction wave travel through the thickness of the top plate of the sandwich. The shock wave is produced by detonation of the explosive layer in contact with the plate and rarefaction is generated when the shock wave is released at the free surface of this plate. Since the velocity of both these waves has been assumed approximately equal, and each wave takes a time dp/U_s , the total time of travel for both waves is

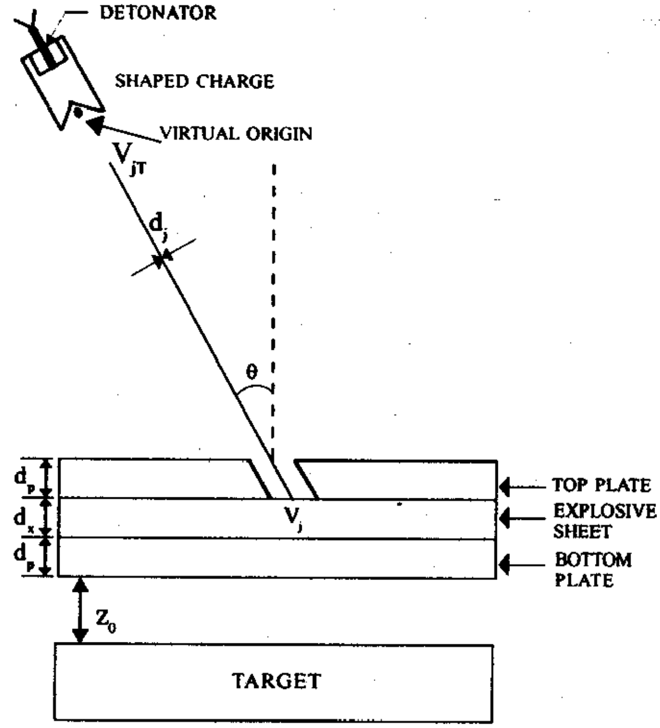

Figure 2. Jet penetration of top plate of the sandwich at time, $t_0 < t < (t_1 + t_0)$.

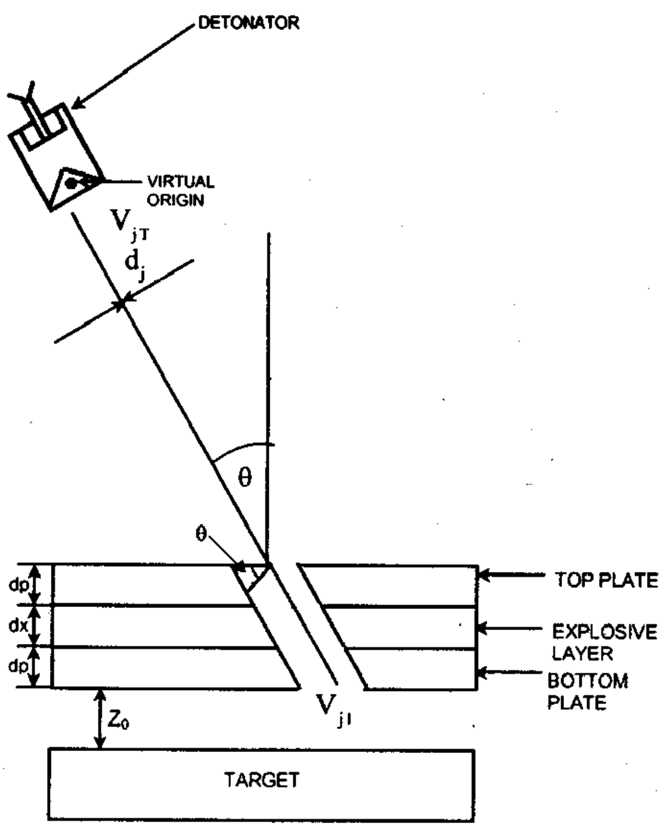

Figure 3. Jet penetration and detonation of the sandwich at time, $t = t_1 + t_0$.

$2dp/U_s$. The penetration of the top plate and the complete sandwich by the jet is shown in Figs 2 and 3, respectively. During this time, the hole in the top plate continues to expand. To ascertain this fact, it is essential to determine the rate of crater expansion and the time for achieving its maximum radius.

3.1 Rate of Crater Expansion

If R_t and ρ_t indicate the dynamic yield strength and density of the top metal plate of the ERA sandwich, respectively, then according to Szendrei[6] relation, the variation of crater radius R_c with time is obtained as

$$R_c^2 = \frac{A}{B} - \left[\left(\frac{A}{B} - R_j^2\right)^{\frac{1}{2}} - t(B)^{\frac{1}{2}}\right]^2 \qquad (2)$$

where

$$A = \frac{R_j^2 V_{j0}^2}{2\left(1 + \sqrt{\frac{\rho_t}{\rho_j}}\right)^2} \qquad B = \frac{R_t}{\rho_t}$$

and R_j is the jet radius.

The maximum crater radius, is therefore, obtained as

$$R_{CM} = \sqrt{\frac{A}{B}} \qquad (3)$$

and the time in which this maximum radius is achieved is given as

$$t_f = \frac{\sqrt{\frac{A}{B} - R_j^2}}{\sqrt{B}} \qquad (4)$$

It is clear from these relations that the expansion rate (U_c) decreases with time and the final diameter of the hole is attained without further expansion only at a time t_f. If $R_j = 0.1$cm, $U_{av} = 3$ mm/µs, $\rho_t = 7.85$ g/cc and $R_t = 5 \times 10^9$ dynes/cm², then Eqn (4) yields the value of $t_f = 33$ µs. It is therefore assumed that the formation of the final hole diameter is not complete in time $t_1 = 2$ µs which approximately is the time for penetrating the sandwich as obtained from Eqn (1). Under these conditions, the movement of the plate and the expansion of the hole radius occur simultaneously and both are time-dependent. To determine the instant of time, when the transversal shifting of the jet due to plate motion makes the jet reach the wall of the hole, one needs to derive a relation for plate velocity and distance moved by the plate under explosive loading as a function of time.

3.2 Plate Velocity under Explosive Loading

Aziz[7], *et al.* studied the motion of a rigid metal plate by a cylindrical explosive charge. The final velocity of the plate was obtained as a function of C/M. A similar approach has been used in this analysis for getting plate velocity as a function of time for the sandwich geometry of the ERA. The length of the charge has been taken as half of the explosive layer thickness in case of symmetrical sandwich. Making basic assumptions, similar to those of Aziz, *et al.*, following set of equations can be solved to obtain velocity and distance of the plate as

$$P = M\frac{du}{dt} \tag{5}$$

$$u + c = \frac{x}{t} \tag{6}$$

$$PV^{\gamma} = \text{Constant}$$

where u and M denote velocity and mass per unit area of the plate. P, V, c and γ represent pressure, volume, sound velocity and adiabatic exponent of detonation products, respectively. The distance and time coordinates are denoted by x and t with point of initiation as the origin. If u_j, c_j and D denote particle velocity, sound velocity and detonation velocity at C–J plane, respectively, then Chapmann–Joguet (C–J) condition $u_j + c_j = D$ provides the boundary conditions for plate motion as $u = 0$ and $c = c_j = D$ at $x = L$ and $t = L/D$, where $2L$ is the thickness of the explosive. Aziz[7], *et al.* have obtained the expressions for the plate velocity u, as

$$u = \frac{4a}{b^2}\left[\frac{\left(\frac{L}{D}-\frac{b}{2}\right)}{\left\{\left(\frac{L}{D}-\frac{b}{2}\right)^2-\left(\frac{b}{2}\right)^2\right\}^{\frac{1}{2}}} - \frac{\left(\frac{L}{D}+T-\frac{b}{2}\right)}{\left\{\left[\frac{L}{D}+T-\frac{b}{2}\right]^2-\left(\frac{b}{2}\right)^2\right\}^{\frac{1}{2}}}\right] \tag{7}$$

where

$$a = \frac{\frac{16}{27}\frac{C}{M}\frac{L^2}{D}}{\left(1+\frac{32}{27}\frac{C}{M}\right)^{\frac{3}{2}}}$$

and

$$b = \frac{32}{27}\frac{C}{M}\frac{L}{D}\Big/\left(1+\frac{32}{27}\frac{C}{M}\right)$$

At time, $t = \infty$, the plate velocity expression is reduced to the form

$$U_f = \frac{Z-1}{Z+1}D \tag{8}$$

where

$$Z = \left(1+\frac{32}{27}\frac{C}{M}\right)^{\frac{1}{2}}$$

which is the relation for final velocity of the plate obtained by Aziz[7], *et al.* It is obvious from plate velocity relation [Eqn (7)] that the plate attains its final velocity asymptotically. Integrating Eqn (7), one gets the relation for distance moved by the plate as

$$Y=A_1T-B_1\left[\left\{\left(1+T-\frac{b}{2}\right)^2-\left(\frac{b}{2}\right)^2\right\}^{\frac{1}{2}}-\left\{\left(\frac{L}{D}-\frac{b}{2}\right)^2-\left(\frac{b}{2}\right)^2\right\}^{\frac{1}{2}}\right] \quad (9)$$

where T represents the time of flight of the plate

$$A_1 = \frac{D\left(1+\frac{16}{27}\frac{C}{M}\right)}{\frac{16}{27}\frac{C}{M}}$$

and

$$B_1 = D\,\frac{\left(1+\frac{32}{27}\frac{C}{M}\right)^{\frac{1}{2}}}{\frac{16}{27}\frac{C}{M}}$$

In this relation, $Y = 0$ at time $T = 0$. It is clear from these relations, that the distance moved by the plate during the acceleration phase depends on both C/M, and L/D ratios. The final velocity of the plate however depends on C/M only.

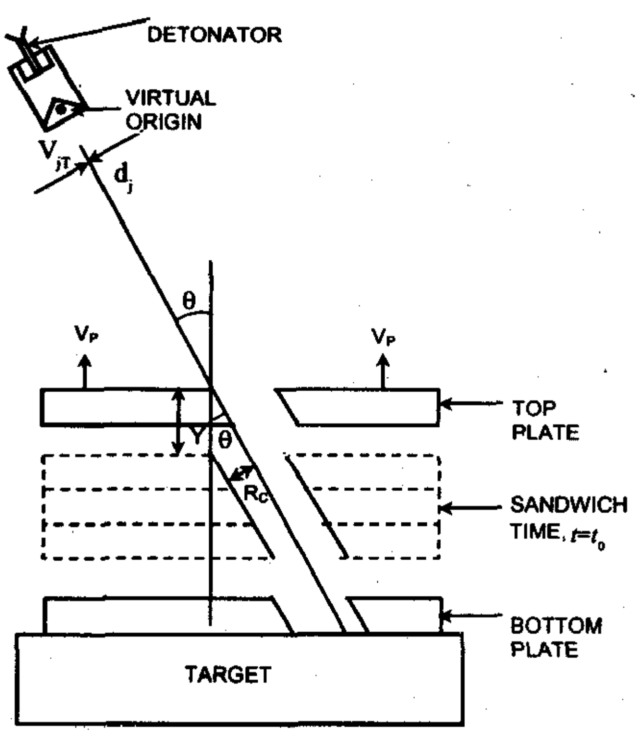

Figure 4. Jet interruption due to motion of top ERA plate at time, $t = t_0 + t_1 + T$.

3.3 Time of Jet Interaction with Crater Edge

The movement of plate shifts the position of the jet laterally from the centre to the wall of the hole as shown in Fig. 4. If the plate moves a distance Y in time T, then the jet shifts by a distance R_S, which is obtained by geometrical analysis of Fig. 4 as

$$R_S = Y \sin\theta \quad (10)$$

Substituting the value of Y from Eqn (9), one gets the relation for R_S as a function of time. Remembering that the formation of crater started at time t_1 earlier to the commencement of plate motion, one can substitute $t_1 + T$ for time in Eqn (2) and then solve it with Eqn (10) to determine the time of jet interruption, T_c, by the wall of the crater.

Figure 5 shows the graphical method for solving Eqns (2) and (10) simultaneously. Values of R_S obtained from these relations are plotted as a function of time on the same graph. The point of intersection then yields the value of time T_c. While drawing these graphs it is important to note that if $R_S = 0$ at $t = 0$, then value of R_C at $t = 0$ is equal to the crater radius produced in time t_1.

3.4 Length of Undisturbed Jet

If the jet impacts on the sandwich at an angle θ with its normal, it has to penetrate a thickness 2 dp secθ in the metal plate and dx secθ in the explosive in the direction of the jet to cross the sandwich. If V_{j1}, V_{jx}, V_{j2} are the velocities of the jet elements that emerge out of the other side of top plate, explosive layer and the bottom plate of the sandwich, then

$$V_{j1} = \frac{V_{j0}}{\left(1+\frac{dp\,\sec\theta}{S_0}\right)^{\frac{1}{\gamma_p}}} \quad (11)$$

$$V_{jx} = \frac{V_{j1}}{\left(1 + \frac{dx \sec\theta}{S_0 + dp \sec\theta}\right)^{\frac{1}{\gamma_x}}} \quad (12)$$

and

$$V_{j2} = \frac{V_{jx}}{\left(1 + \frac{dx \sec\theta}{S_0 + (dp + dx)\sec\theta}\right)^{\frac{1}{\gamma_p}}} \quad (13)$$

$$\gamma_p = \sqrt{\frac{\rho_j}{\rho_p}} \quad \text{and} \quad \gamma_x = \sqrt{\frac{\rho_j}{\rho_x}}$$

where ρ_p, ρ_j, ρ_x are the density of plate, jet, and explosive material, respectively. The time taken by the jet to penetrate the sandwich can be obtained from the relation

$$t_j = \frac{S_0 + (dx + 2dp)sec\theta}{V_{j2}} - \frac{S_0}{V_{j0}} \quad (14)$$

as V_{j2} is known from Eqn (13) and V_{jx} from Eqn (12). The top plate of the sandwich now starts moving towards the jet and the bottom plate starts moving away from the jet. The time for jet interruption by top plate only is considered relevant for the present analysis as the bottom plate is close to the target and comes to rest before the jet interruption. If the jet shifts to the wall of the crater in top plate, in time T and the plate moves the distance Y during this time, then the velocity of the last element of the jet which passes out of the sandwich undisturbed, is obtained as

$$V_{jc} = \frac{S_0 + (dp - Y)\sec\theta}{t_0 + t_1 + T} \quad (15)$$

Since the length of the jet passing out of the hole in top plate lies between exit velocities, viz., V_{j2} and V_{jc}, one can calculate the depth of penetration in the target at a stand-off ($S_0 + Z_0 \sec\theta$) from the relation

$$P_j = (S_0 + Z_0 \sec\theta)\left[\left(\frac{V_{j2}}{V_{jc}}\right)^{\gamma_T} - 1\right] \quad (16)$$

where

$$\gamma_T = \left(\rho_j / \rho_T\right)^{\frac{1}{2}}$$

4. RESULTS & DISCUSSION

The magnitude of crater radius (R_C) in the sandwich plates of mild steel and aluminium at different time intervals after the instant of jet impact on the top plate of the sandwich has been calculated using constants of Table 1 in Eqn (2). It has been

Table 1. Input parameters for calculation of R_c and R_s curves and jet penetration

(a) *Plate Parameters*

Parameters	Aluminium	Aluminium alloy	Mild steel
Density ρ_p (g/cc)	2.785	2.785	7.85
Thickness dp (cm)	0.1	0.1	0.1
Dynamic strength (dyne/cm²)	1x10⁹	5x10⁹	5x10⁹
Stand-off from target Z_0 (cm)	2	2	2

(b) *Jet Parameters*

Parameters	Values
Density [ρ_j (g/cc)]	8.9
Diameter [d_j (cm)]	0.2
Tip velocity [V_{j0} (cm/s)]	9 X 105
Stand-off distance [S_0 (cm)] between virtual origin and impact point of jet	34
Angle of attack (deg)	60

(c) *Explosive Parameters*

Parameters	Values
Density [(ρx) g/cc]	1.2 8
VOD [D (cm/s)]	7.3 X10[5]
Thickness [2L (cm)]	0.1–1.5

assumed that the jet of similar characteristics impacts on both the sandwiches. The values of resistance to penetration, given in Table 1, are arbitrary dynamic strengths of these materials. The crater radii obtained from these calculations are plotted as a function of time in Figs 5 and 6 as R_C curves. While plotting these curves the initial value of crater radius is taken equal to the radius of the shaped charge jet. These crater radii versus time curves clearly show that the slope of the curves decreases monotonically with time till the radius of curvature attains its maximum value. The rate of increase of R_C in aluminium is higher than that in mild steel. Further when the jet of 9 mm/μs impacts the sandwich of aluminium and mild steel plates, the time required by the crater to attain its final radii in mild steel and aluminium are given as 51μs and 111 μs, respectively. One can expect this due to the difference of shock pressures generated by jet impact in aluminium and mild steel plates and also the difference in dynamic resistance offered by these materials to crater expansion.

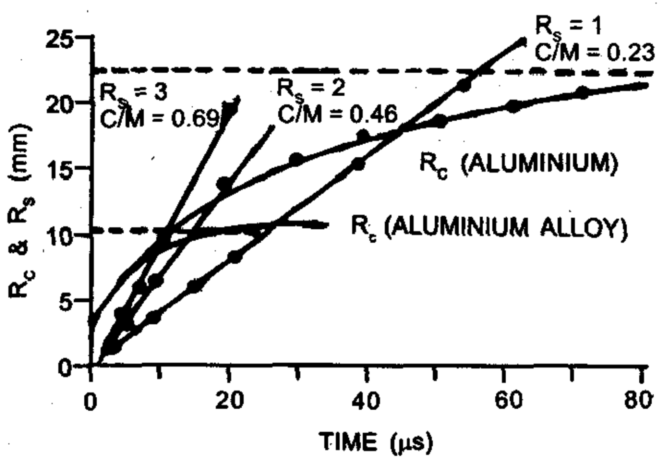

Figure 5. Jet interruption by the growing crater in aluminium and aluminium alloy plates of 1mm thickness.

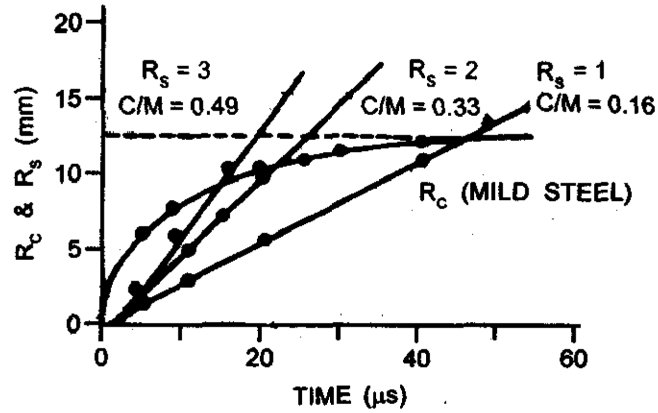

Figure 6. Jet interruption by the growing crater in mild steel plates of 1mm thickness.

To obtain lateral shift (R_S) in the position of the jet, it has been noted that the top plate of sandwich starts its movement only at a time 2 dp/U_s after first impact of the jet on the surface of the explosive layer of the sandwich. The distance moved by the plate (Y) has first been obtained from Eqn (9) for different values of C/M of the

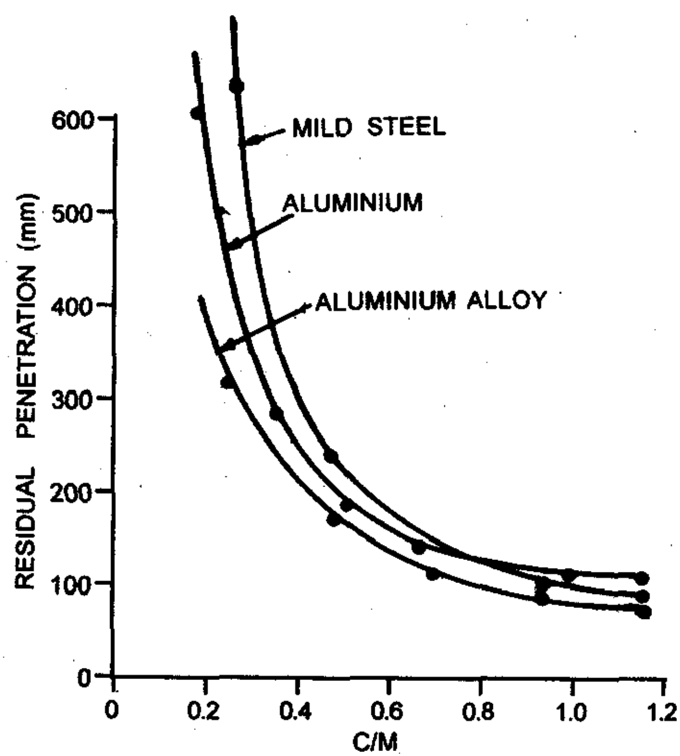

Figure 7. Jet penetration as function of C/M of sandwich plates of different materials.

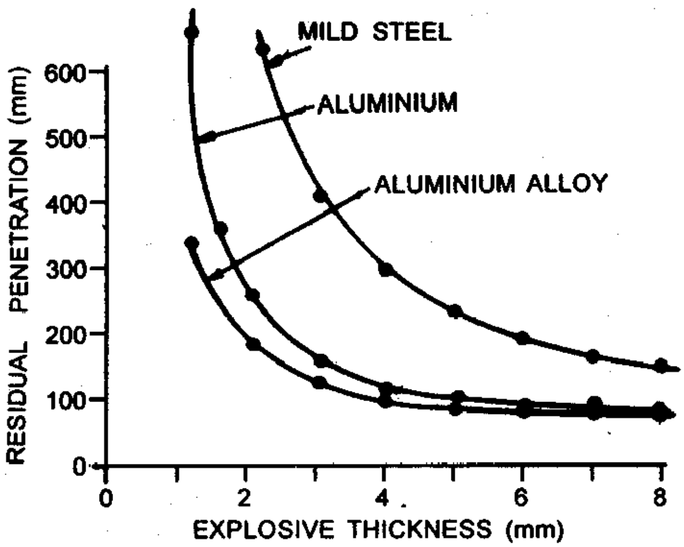

Figure 8. Jet penetration as function of explosive thickness of ERA sandwich plates of different materials.

sandwich. The values of distance Y have then been used in Eqn (10) to obtain shift of the jet (R_S) at different time intervals. These values have been plotted in Figs 5 and 6 as straight lines cutting the time axis at $t = 2dp/U_s$. One can see in these figures that $R_C(t)$ curve intersects all the $R_S(t)$ straight lines. The points of intersection of $R_S(t)$ and, $R_C(t)$ curves yield the time (T_c) and radius of the crater R_c where the jet first touches the edge of the crater. The jet passes out of the plate undisturbed during time interval (T_c- t_j), where t_j is the time taken by the jet to penetrate the sandwich. After this time interval, the jet gets disturbed and loses its power to penetrate the target. The slope of $R_S(t)$ curves increases with the increase of plate velocity, and consequently intersects the $R_c(t)$ curve earlier. It is therefore clear that fast moving sandwich plate allows the free passage of the jet for lesser time and thus, such plates when used in the ERA sandwich, makes the ERA more efficient.

It is important to note that the movement of the plate results in lateral shifting of the jet inside the crater and in all cases considered in this analysis, the jet touches the crater wall much before the completion of crater formation. It is obvious from curves of Figs 5 and 6 that all $R_S(t)$ curves intersect the rising part of the $R_c(t)$ curve and none of the three $R_S(t)$ curves cut the horizontal portion of $R_c(t)$ which represents the formation of the final diameter of the crater.

If the tip velocity of the jet, going out of the sandwich after its penetration, is V_{j2} and the velocity of the last element of the jet which goes out of the sandwich at time T_c, when the jet touches the wall of the hole is V_{jc}, then the penetration due to the jet length existing in between these two elements of velocity V_{j2} and V_{jc} has been obtained from Eqn (16). Figure 7 shows the residual penetration of this jet length in mild steel target across mild steel and aluminum ERA sandwiches. Mild steel plate produces lower penetration as compared to aluminium plate. However, aluminium alloy produces the lowest residual penetration. These features of ERA sandwiches of different metal plates are clearly seen in Figs 7 and 8. The basic reason for comparative performance of these ERA sandwiches lies in the competitive mechanisms occurring in plate acceleration or equivalently, rate of jet shifting and crater formation in these materials. Mild steel plate, though stronger and of higher density, accelerates to lesser plate velocities as compared to that of aluminium plate of the same thickness when accelerated by an equal thickness of the explosive. However, in aluminium plate, both the rate of crater formation and the shifting of jet are faster, while in aluminium alloy, the rate of jet shifting is high but rate of crater formation is slow due to its higher strength. It is clear from Fig. 7 that the residual jet penetration decreases with increase in plate velocity, and therefore, the efficiency of ERA sandwich increases with increase of C/M of the sandwich. It holds good for the sandwiches of both aluminium and mild steel plates.

To examine the effect of strength of sandwich plates on efficiency of the ERA, the residual penetration of the shaped charge jet has been calculated across an ERA sandwich, which has metal (alloy) plates of five-times more strength than that of aluminium but the density is equal to that of aluminium. Variation of this penetration with C/M and explosive thickness have been shown in Figs 7 and 8, respectively. These curves show that the strength of metal plates increases the efficiency of ERA. It is thus clearly seen that the efficiency of ERA sandwich depends on both the strength of the metal plates and their velocities which, in turn, are controlled by the C/M ratios of the sandwich.

5. CONCLUSION

The paper provides a simple analytical model to study the dependence of performance of ERA on the plate and the crater expansion velocity. It has been assumed in this analysis that the amplitude of disturbance to jet by ERA is too high to cause any penetration in the target, and therefore, the penetration due to disturbed jet can be neglected. This study shows that the performance of ERA against typical jet at a particular angle of impact improves with increased velocity and strength of sandwich plates.

ACKNOWLEDGEMENTS

The author expresses his sincere thanks to Dr Haridwar Singh, Director, High Energy Materials Research Laboratory (HEMRL), Pune for his inspiration throughout this work and permission to publish this paper. Thanks are also due to Sarvashri P.V. Kamat, S.E. Bhusare, S.L. Jawale and Mrs. S.V. Divate for their efforts in the preparation of this manuscript.

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