ISO-CONTOUR MAPS FOR BALLISTIC PERFORMANCE OF THICK METALLIC ARMOUR

B. Srivathsa and N. Ramakrishnan*

Computer modelling and simulation centre, DMRL, Hyderabad, India.
*Director, RRL, Bhopal, India.

E-mail: bsv@indiainfo.com, bsv@dmrl.ernet.in

Extended abstract

The ballistic resistance of an armour material is normally characterized in terms of the reciprocal of the areal density of the target material that is required to arrest a particular type of projectile with a specific velocity. The development of such metallic armour material requires a large number of experiments for different alloy compositions and also heat treatment processes. With regard to ballistic properties a little is known on increasing the mechanical properties with alloy composition and heat treatment. This in our opinion is due to lack of proper correlation between the mechanical properties and the ballistic performance. An attempt made in this direction is, a ballistic performance index developed by Srivathsa and Ramakrishnan [1,2]. The index is developed on energy balance approach in a two-stage penetration and expressed in terms of the static mechanical properties and striking velocities of the projectile. Using this index ballistic performance maps are generated for steel, aluminium and titanium alloys. These maps are iso-performance contours as a function of the yield strength and the strain-hardening rate for a given striking velocity. The present investigations are mainly concerned with the effect of the mechanical properties, which in turn are related to the metallurgical processes. This aspect makes the ballistic performance maps ideal ready reckoners for developing as well as selecting metallic armour. The maps provide iso-performance contours as a function of the yield strength and the strain-hardening rate for a given striking velocity. The maps generated for steel, aluminium and titanium alloys are validated with experimental results.

In this model, the kinetic energy of the projectile is assumed to be absorbed by an armour plate of finite thickness in three different modes:

(a) the elastic deformation of the material

(b) the plastic deformation of the material

(c) the kinetic energy imparted to the target material.

The energy dissipation demarks the finite thickness of the armour plate into two regions. At the striking face of the target, the region (I) is assumed to be in the plane strain condition, and the material flows only in radial direction. At the other end (II), the material is assumed to bulge in bringing the projectile to rest. The relative widths of these two regions are computed based on a typically observed velocity decay of the projectile during the penetration. The total energy absorbed in each of the above cases is determined as the product of the energy absorbed per unit volume and participating in the respective mode of deformation. The volume that participates in any mode of deformation is computed using the distance covered by the elastic or the plastic wave front propagating in radial direction from the line of penetration.

1. Ballistic performance Index

The energy per unit areal density absorbed by the target material by all the three modes discussed in the above section has been shown to be [2]:

$$\frac{\psi}{\rho d} = \pi^2 v_r^4 \left[\frac{\alpha_I}{2(1+k_b)^2} + \alpha_{II} \frac{(1+k_e)^2 k_v^2}{2k_j^2} + \frac{1}{k_j}\left(1+\frac{1}{k_p}\right) + \frac{1}{2k_p^2} + \frac{1}{2}\left(1+\frac{1}{k_p}\right)^2 \right] \qquad (1)$$

The terms α_I and α_{II} are the fractional widths of the constrained (I) and the unconstrained (II) regions respectively. The non-dimensional parameter k_e, k_p, k_j, k_b, and k_v can be computed from the following relations:

$$k_v = \sqrt{\frac{1-\nu}{(1-2\nu)(1+\nu)}} \qquad k_b = v_r\sqrt{\frac{\rho}{K}} \quad \text{where } k = \frac{E}{3(1-2\nu)}$$

$$k_e = \frac{v_r}{k_v}\sqrt{\frac{\rho}{E}} \qquad k_p = v_r\sqrt{\frac{\rho}{E_p}} \quad \text{where } E_p = \frac{\sigma_u(1+\varepsilon_r) - \sigma_y}{\varepsilon_r}$$

$$k_j = \frac{\rho v_r^2}{\sigma_y}$$

$$\alpha_I = 1 - \alpha_{II} = 1 - \sqrt{\frac{v_1}{v_0}} \quad \text{where } v_1 = \frac{-k_v\sqrt{\rho E} + \sqrt{k_v^2 E\rho + 10.4\rho\sigma_y}}{2\rho}$$

where ρ is the density, E the elastic modulus , σ_y the yield strength, σ_u the tensile strength, ν the Poisson's ration, ε_r the reduction in area or the fractional elongation and v_0 is the striking velocity, v_r is a material and thickness independent representative or average velocity defined as $v_r = v_0/1.85$. For more details the reader is advised to refer to Ref. [1,2]. In Eq,(1) it can be seen easily that the terms inside the square bracket corresponds to the mechanical properties as well as the striking velocity.

Therefore, the ballistic performance index (BPI) can be expressed as

$$\phi = \left[\frac{\alpha_I}{2(1+k_b)^2} + \alpha_{II}\frac{(1+k_e)^2 k_v^2}{2k_j^2} + \frac{1}{k_j}\left(1+\frac{1}{k_p}\right) + \frac{1}{2k_p^2} + \frac{1}{2}\left(1+\frac{1}{k_p}\right)^2 \right] \qquad (2)$$

On the RHS of Eq.(2) the first two terms represent the elastic components, the third and fourth terms represents the plastic components and the last terms corresponds to the kinetic energy component. Since all these terms are dimensionless ϕ is also a dimensionless parameter. In all of the presented results, the index has been normalized with respect to that of mild steel for a quick appraisal of the ballistic quality.

2. Ballistic performance maps

The ballistic performance index (BPI), expressed in the form of Eq. (2) is a function static mechanical property like modulus, density, yields strength, ultimate strength and fracture strain. It quickly helps in assessing armour quality of metallic materials. However, the alien nature of the subject and its complex algebraic form may be cumbersome for calculating the index. Therefore, to provide a quick and graphical appraisal of the ballistic quality ballistic performance maps (BPMs) are generated. The iso-BPI contours are generated of steel, aluminium and titanium alloys provide a general idea about the importance of the strain-hardening rate. These generic BPMs for four different striking velocities are used to demonstrate the capability and use of these maps.

3. Validation and conclusions

For verifying the accuracy of the maps, the experimental results published by Madhu [17] and Dikshit and co-workers [18,19] were used. The predictions are satisfactory. This paper presents a concept of generating ballistic performance maps to assess the ballistic quality of metallic materials using static mechanical properties. These maps are generated using a ballistic index of metallic materials (steel, aluminium and titanium) and normalised with ballistic index of mild steel. The simplicity and applicability of these maps will facilitate the development activity pertaining to metallic armour and its use can be further extended for designing functionally gradient metallic armour by suitably adapting the established procedure.

References

[1] B. Srivathsa, N. Ramakrishnan, on the ballistic performance of metallic materials, Bull mater. Sci. 19 (1997) 1-13.

[2] B. Srivathsa, N. Ramakrishnan, on the ballistic performance index for thick metallic armour, Comp. Simulation Modelling in Engg. 3 (1998) 33-40.

[3] W.T. Thompson, An approximate theory of armour penetration, J. Appl. Phys. 26 (1995) 80-82.

[4] R.F. Recht, Catastrophic thermo-plastic shear, J. Appl. Mech. 1 (1964) 189-193.

[5] J. Manganello, K.H. Abbot, Metallurgical factors affecting the ballistic behaviour of steel targets, J. Mats, JMLSA 7 (1972) 231-239.

[6] A.L. Wingrove, G.L. Wulf, Some aspects of target and projectile on penetration behaviour , J. Aust. Inst. Met 18 (1973) 167-173.

[7] J. Awerbuch, S.R.Bodner, Analysis of mechanics of perforation of projectiles in metallic plates , Int. J. Solids Struct. 10 (1971) 671-684.

[8] A. Tate, A possible explanation for the hydrodynamic transition in high speed impact, Int. J. Mech. Sci. 19 (1977) 121-123.

[9] R.L. Woodward, the penetration of metal targets which fail by a adiabatic shear, Int. J. Mech. Sci. 20 (1978) 559-607.

[10] M.E. Backman, W. Goldsmith, The mechanics of penetration of projectiles into targets, Int. J. Engg. Sci. 16 (1978) 1-99.

[11] G.H. Jane, J.A. Zukas, Mechanics of penetration, Int. J. Engg. Sci. 16 (1978) 879-903.

[12] M. Ravid, S.R. Bodner, Dynamic perforation of viscoplastic plates by rigid projectiles, Int. J. Engg. Sci. 21 (1983) 577-591.

[13] R.S.J. Corran, P.S.J Shadbolt, C. Ruiz, Impact loading of plate; an experimental investigation, Int. J. Impact. Engg. 1 (1983) 3-22.

[14] B.L. Landkof, W. Goldsmith, petalling of thin metallic plates during penetration by cylindro-conical projectiles, Int. J. Solids. Struct. 21 (1985) 245-266.

[15] M.J. Forrestal, Z. Rosenberg, V.K. Luk, S.J. Bress, Perforation of Al plates with conical nosed rods, Trans. ASME 54 (1987) 230-232.

[16] J. Randin, W. Goldsmith, Normal projectile penetration of layered targets, Int. J. Impact. Engg. 7 (1988) 229-259.

[17] V. Madhu , Impact of kinetic energy projectiles on single and layered plates, Ph.D Thesis, Indian Institute of Technology, New Delhi, India, 1994.

[18] S.N. Dikshit, G. Sundararajan, The penetration of thick steel plates by ogive shaped projectiles – experimental & investigation, Int. J. Impact. Engg. 12 (1992) 373-407.

[19] S.N. Dikshit, V.V. Kutumba Rao, G. Sundararajan, The influence of plate hardness on the ballistic penetration of thick plates, Int. J. Impact. Engg. 16 (1995) 293.

[20] The resistance of various metallic materials to perforetion by steel fragments; empirical relationships for fragment residual velocity and weight, Technical Report Project THOR TR No.47, 1961 and No.51, 1963, Ballistic Research Laboratory, Aberdeen Proving Ground, Washington state, USA.

[21] A.S.M. Smithells, Metals reference book, 6th ed., Butterworths, London, 1983.

[22] A.S.M. Smithells, Metals reference book, 3rd ed., Materials Information Society, Ohio, USA, 1993.

[23] N. Ramakrishnan, Ballistic test procedures for armour materials, Technical Report DMRL, Hyderabad, India, 1986.