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MARIBYRNONG VICTORIA

REPORT

MRL-R-675

CRITERIA FOR THE SELECTION OF HOMOGENEOUS METAL ARMOUR

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JAN 14 1977
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R. L. Woodward

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ABSTRACT

A method is described which allows an assessment of the relative numerical values for thickness, weight and cost of homogeneous metal armour to defend a unit area against non-deforming, armour piercing type projectiles. The mode of failure described by the model is ductile hole formation and acceptable results are also obtained if failure is by dishing or plugging.

Typical data are presented for a variety of prospective materials and criteria for the choice of appropriate armour are discussed.

The superior ballistic performances of titanium alloys and Hadfield's steel are highlighted.

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CRITERIA FOR THE SELECTION OF HOMOGENEOUS METAL ARMOUR

1. INTRODUCTION

In order to establish criteria for the selection of homogeneous metal armour it is necessary to relate the penetration resistance to the cost of the armour material. In this report a correlation is used between the mechanical properties of the armour material and the resistance to penetration by armour piercing projectiles so as to relate the thickness, weight and cost of armour to defend a unit area against a specified threat. Using this correlation the performance of a range of homogeneous armour materials is compared.

2. MODEL OF PENETRATION RESISTANCE

Three of the most common modes of failure experienced by homogeneous metal armour, i.e. ductile hole formation, dishing and plugging, are illustrated in Fig. 1. A common characteristic of these failure modes is that they exhibit considerable plasticity and hence an estimate of the work done in plastic flow should give a reasonable guide to the energy required to defeat the target. The kinetic energy of a projectile which just defeats a target by the ductile hole formation mode is equal to the work done in expanding a hole in the target from zero to the projectile diameter[1] and the appropriate relation is

$$\frac{1}{2} m V_o^2 = \pi \frac{D^2}{2} \sigma_o h \qquad (1)$$

where m is the projectile mass,

V_o is the minimum projectile velocity to defeat the target,

D is the projectile diameter,

h the target thickness and,

σ_o an appropriate strength parameter for the target material.

It has been found that equation (1) also gives acceptable results when treating either the dishing or the plugging modes of failure[1] over a wide range of conditions and hence the equation can be used generally to match target strength and thickness to the projectile mass, velocity and diameter.

In the plasticity problem for the defeat of a metal target the strains involved are large and hence the appropriate strength parameter (σ_o) is the compressive yield stress at some high value of strain. In the present instance (see also reference 1) values of uniaxial flow stress at a natural strain of 1.0 have been used and these values are obtained by extrapolating the results of uniaxial compression tests to a natural strain of 1.0. At this level of strain the flow stress of metals is generally insensitive to further increases in strain.

Using equation (1) the thickness of armour (h) to just match a known threat is

$$h = \frac{mV_o^2}{\pi D^2} \frac{1}{\sigma_o} \qquad (2)$$

The areal density (A) (mass of armour per unit area) to match this threat is simply

$$A = \rho h = \frac{mV_o^2}{\pi D^2} \frac{\rho}{\sigma_o} \qquad (3)$$

where ρ is the density of the target material. The cost to defend a unit area (C) is the cost per unit mass of target material (K) times the mass per unit area (A)

$$C = KA = K\rho h = \frac{mV_o^2}{\pi D^2} \frac{K\rho}{\sigma_o} \qquad (4)$$

Thus the thickness (h), areal density (A) and cost per unit area (C) to defend with different homogeneous metal armour materials can be simply compared using the parameters $1/\sigma_o$, ρ/σ_o and $K\rho/\sigma_o$ respectively; good estimates for actual values can be obtained by multiplying by the projectile threat parameter $mV_o^2/\pi D^2$ in the appropriate units. The accuracy of the result depends on the reliability of equation (1).

When using equation (1) to calculate critical velocities for the defeat of targets it is found that the calculated velocity is generally 80 to 90 per cent of the experimental critical velocity. The discrepancy arises because equation (1) only accounts for the most significant mode of energy consumption, plastic flow, and several secondary terms which depend on the target material are ignored; for example friction and inertia. Because the critical velocity is underestimated target thicknesses, areal densities and costs per unit area determined using equations (2), (3) and (4) will be conservative. When determining actual values for the parameters h, A and C the appropriate result will be between 65 and 80 per cent of the calculated value from equations (2), (3) and (4) respectively. A more accurate determination than this requires experiment. Relative material performance can still be judged by comparing $1/\sigma_o$, ρ/σ_o and $K\rho/\sigma_o$ for h, A and C respectively.

3. COST AND WEIGHT EFFECTIVENESS OF HOMOGENEOUS METAL ARMOUR MATERIALS

Table I lists a range of prospective homogeneous metal armour materials with their appropriate Vickers hardness and the basic parameters σ_o, ρ and K together with the derived parameters $1/\sigma_o$, ρ/σ_o and $K\rho/\sigma_o$. In each case the Vickers hardness can be used as an indicator of the material condition, i.e. if the material has the specified Vickers hardness then the value of σ_o should be close to the typical value given for the material in Table I. There is however no simple relationship between Vickers hardness and σ_o value which can be applied universally to groups of different metals. Thus in practice it is essential to determine σ_o values by compression tests. The σ_o and Vickers hardness values in Table I were obtained on the same metal samples and are indicative of the properties to be obtained in the types of materials specified.

For the material density (ρ) standard text values were generally used. The cost per unit mass (K) was obtained by surveying Australian suppliers for quotations on the sheet material in thicknesses varying from 6.0 to 50 mm; the values given are typical. In one case (SAE 4130 steel) the price varied considerably and two limits are given. For two materials, unavailable in Australia at the present time, prices are unattainable but the other data is included to give an indication of improvements in performance which may be obtained.

In comparing the armour materials the objective is generally to minimise the thickness factor ($1/\sigma_o$), the weight factor (ρ/σ_o) and the cost factor ($K\rho/\sigma_o$). Not all of these factors will be low in the one material and therefore some appropriate weighting must be assigned to each, depending on the application. Nevertheless some relevant comments can be made on the basis of the data in Table I.

Clearly the least costly material for protection is hot rolled mild steel, however use of this material carries a severe weight penalty. The hardness of mild steel can be increased by cold work but the σ_o value and hence the penetration resistance is not increased significantly by this method. Heat treatment hardening of mild steel will increase σ_o and hence penetration resistance thus reducing the weight factor, however the hardenability of mild steel is low and heat treatment is only successful in thin sections.

The problem of hardenability is overcome with the use of alloy steels which can be successfully heat treated in thick sections. The low alloy SAE 4130 type steel is similar to typical armour steels and although it is significantly more expensive than mild steel the weight disadvantage is reduced. Increasing the hardness of the 4130 type steel reduces both the weight and cost factors considerably, however it is found in practice that hardnesses above approximately 350 HV are impractical in commercial homogeneous steel armour[2]. The mode of failure changes at these hardnesses and penetration resistance drops off due to the influence of adiabatic shear on plugging failure of the target.

In terms of both weight and cost the P8 Hadfield's steel appears to offer considerable advantages. The main problems with this material lie in fabrication as it is particularly difficult to machine. This material is used in some armour applications, for example army helmets and security vans.

The cost and weight factors for the 5083 aluminium alloy are similar to the values for the 4130 steel. In applications where the projectile threat, $\frac{mV^2}{\pi D^2}$, is large the thickness of this aluminium would be excessive. However, where the thickness of aluminium armour required also allows its use as a structural component, for example in the M113 armoured personnel carrier, significant weight reductions are possible. The higher strength 7039 aluminium alloy offers a substantial improvement in weight; however this alloy is not at present produced in Australia and no cost estimate could be obtained. Actual thicknesses, weights and costs for these aluminium alloys can be more accurately specified and are invariably found to lie close to 0.65 times the values found from Table I.

Commercial purity titanium does not offer a substantial weight saving and has a high cost factor, however the titanium alloys tested (318 and 8Al-1Mo-1V) give substantial weight savings. The titanium 318 alloy is very costly but in specialised applications where improved ballistic resistance is required this may be acceptable. No cost information was available on the higher strength titanium alloy but the data would probably be similar to type 318. At present all Australia's titanium requirements are met from imports.

It must be noted, however, that the titanium 318 alloy does not perform up to the merit indicated in Table I. The penetration resistance drops off in thin targets due to the influence of adiabatic shear on plugging failure, as was noted occurs with very hard steel targets. The data derived using equations (2), (3) and (4) and represented in the table is still sufficiently accurate for comparative purposes. A more accurate estimate of the required target thickness for this alloy can be obtained from the equation

$$h = \frac{mV_o{}^2}{\pi D^2} \frac{1}{\sigma_o} + .87\ D \qquad (5)$$

4. PRACTICAL EXAMPLES

Two typical examples of the use of the information given in Table I are for small calibre armour piercing projectiles, viz. .30 Cal. A.P. M2 and .50 Cal. A.P. M2. It was assumed that the projectile would impact at the muzzle velocity and normal to the target plate and thicknesses, areal densities and costs per unit area were calculated by multiplying the threat parameter, $\frac{mV^2}{\pi D^2}$, by $1/\sigma_o$, ρ/σ_o and $K\rho/\sigma_o$ respectively. Tables II and III give the derived data which is conservative as equations (2), (3) and (4) have been used and as noted previously real values will lie between 0.65 and 0.80 times the values given.

The results of Tables I, II and III clearly highlight the superior ballistic performance of two materials, Hadfields steel and titanium alloys. To some extent the superior weight and cost factors with Hadfields steel may be outweighed by fabrication difficulties. The high cost of titanium alloys detracts from their usefulness; however in many cases the high cost can be accommodated, for example where vital components are to be protected in aircraft. Titanium alloys are already used as riot shields by police forces in some countries because of their light weight coupled with good protection.

5. LIMITATIONS OF THE METHOD

A large range of armour applications are not covered by this analysis because the penetration resistance/strength/thickness relationship varies with material type. Face hardened armour, spaced armour, ceramic and textile armour materials are examples of alternatives not covered in this analysis.

If the projectile deforms substantially as is usual with ball shot then the thickness to defeat the threat is greatly overestimated by equation (2). The data of Table I will provide an approximate relative rating of thickness, weight and cost but for more accurate data a suitable model for deforming projectiles is required.

For oblique projectile impact a simple rule, which is conservative, is one proposed by Recht[3] which implies that the increased penetration resistance is dependent on the increased thickness of metal presented to the target. The data shown in Table I is therefore adequate for oblique impact.

As has been pointed out previously, a number of other production and service factors enter into armour selection. In production good weldability, formability and machinability are required as well as a low material cost and in this regard performance will vary with the material type. In service other properties are important besides penetration resistance and weight, e.g. susceptability to corrosion, stress corrosion cracking and brittle fracture.

6. SUMMARY

The method developed allows an assessment of the relative numerical values for the thickness, weight and cost of homogeneous metal armour to defend a unit area against non-deforming armour piercing type projectiles. Typical results are presented for a variety of prospective materials and comments are made on the factors involved in the choice of armour material. The superior performances of titanium alloys and Hadfields steel are highlighted.

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T A B L E I

COMPARISON OF HOMOGENEOUS ARMOUR MATERIALS

Material	Hardness (HV5)	Strength σ_o (Pa) $\times 10^{-6}$	Density ρ (Kg/m^3) $\times 10^{-3}$	Cost K # (\$/Kg)	Thickness Factor $1/\sigma_o$ (Pa^{-1}) $\times 10^9$	Weight Factor ρ/σ_o (Sec^{2}m^{-2}) $\times 10^6$	Cost Factor $\frac{K\rho}{\sigma_o}\left(\frac{\$\ \mathrm{Sec}^2}{\mathrm{Kg\ m}^2}\right)$ $\times 10^6$
Hot rolled CS 1020 mild steel	136	976	7.83	0.24	1.025	8.02	1.89
SAE 4130 Steel (Quenched and Tempered)	300	1240	7.83	2.01-2.65	0.806	6.31	12.7-16.7
	350	1420	7.83	2.01-2.65	0.704	5.51	11.1-14.6
	400	1600	7.83	2.01-2.65	0.625	4.89	9.8-13.0
P8 Hadfields steel (Hot Rolled)	194	1690	7.87	1.02	0.592	4.66	4.75
5083 Aluminium alloy (Cold Rolled)	105	452	2.80	1.90	2.21	6.19	11.8
7039 Aluminium alloy (Aged)	155	638	2.80	-	1.57	4.38	-
Titanium - commercial purity (Mill-annealed)	190	∿ 800*	4.54	12.2	1.25	5.7	69.3
Titanium 318 alloy (Forged and Annealed)	315	1685	4.42	33.05	0.593	2.62	86.6
Titanium 8 Al-1 Mo-1 V alloy (Hot Rolled-annealed)	315	2020	4.42	-	0.495	2.19	-

* Estimate

Data obtained June 1976

TABLE II

HOMOGENEOUS METAL ARMOUR TO DEFEAT

.30 Cal. A.P. M2 PROJECTILES[*]

Material	Hardness (HV 5)	Thickness[ϕ] (mm) (inches in Brackets)	Areal Density[ϕ] (kg/m^2) (lb/ft^2 in Brackets)	Cost per Unit Area[ϕ] (\$/m^2)
Hot Rolled CS 1020 Mild Steel	136	30 (1.2)	239 (49)	56
SAE 4130 Steel	300	24 (.95)	188 (38)	378-497
	350	21 (.85)	164 (34)	331-435
	400	19 (.75)	146 (30)	292-387
P8 Hadfields Steel	194	18 (.70)	139 (28)	142
5083 Aluminium Alloy	105	65 (2.6)	185 (38)	352
7039 Aluminium Alloy	155	47 (1.9)	130 (27)	-
Titanium-Commercial Purity	190	37 (1.5)	170 (35)	2064
Titanium 318 Alloy[#]	315	18 (.70)	78 (16)	2580
Titanium 8 Al-1 Mo-1 V Alloy	315	14 (.60)	65 (13)	-

[*] Threat Parameters - Impact (muzzle) Velocity - 830 m/s
Mass of A.P. Core - 5.25 x 10^{-3} kg
Diameter of A.P. Core - 6.22 x 10^{-3} m

[ϕ] Conservative values from equations (2), (3) and (4). Actual values in range 65 to .80 of those listed.

[#] For Titanium 318 Alloy more accurate thickness values can be obtained from equation (5).

TABLE III

HOMOGENEOUS METAL ARMOUR TO DEFEAT .50 Cal. A.P. M2 PROJECTILES*

Material	Hardness (HV 5)	Thickness[ϕ] (mm) (inches in Brackets)	Areal Density[ϕ] (kg/m^2) (lb/ft^2 in Brackets)	Cost per Unit Area[ϕ] ($\$/m^2$)
Hot Rolled CS 1020 Mild Steel	136	57 (2.3)	449 (92)	105
SAE 4130 Steel	300	45 (1.8)	353 (72)	711-935
	350	39 (1.6)	309 (63)	622-818
	400	35 (1.4)	274 (56)	549-728
P8 Hadfields Steel	194	33 (1.3)	261 (53)	266
5083 Aluminium Alloy	105	123 (4.9)	347 (71)	661
7039 Aluminium Alloy	155	88 (3.5)	245 (50)	-
Titanium-Commercial Purity	190	70 (2.8)	319 (65)	3881
Titanium 318 Alloy[#]	315	33 (1.3)	147 (30)	4850
Titanium 8 Al-1 Mo-1 V Alloy	315	27 (1.1)	123 (25)	-

* Threat Parameters - Impact (muzzle) Velocity - 885 m/s
Mass of A.P. Core - 26.2×10^{-3} kg
Diameter of A.P. Core - 10.8×10^{-3} m

ϕ Conservative values from equations (2), (3) and (4). Actual values in range .65 to .80 of those listed.

\# For Titanium 318 Alloy more accurate thickness values can be obtained from equation (5).

EXAMPLES OF THE THREE PRINCIPAL FAILURE MODES ASSOCIATED WITH THE PENETRATION OF METAL TARGETS

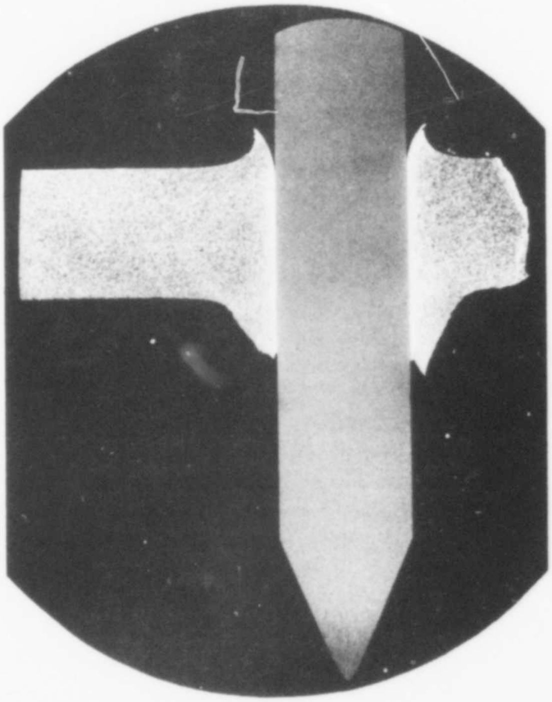

FIG. 1(a) - Ductile hole formation.

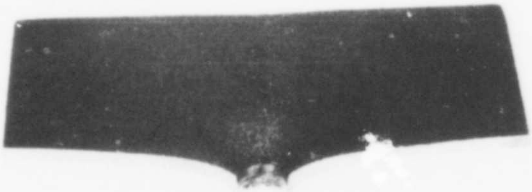

FIG. 1(b) - Dishing.

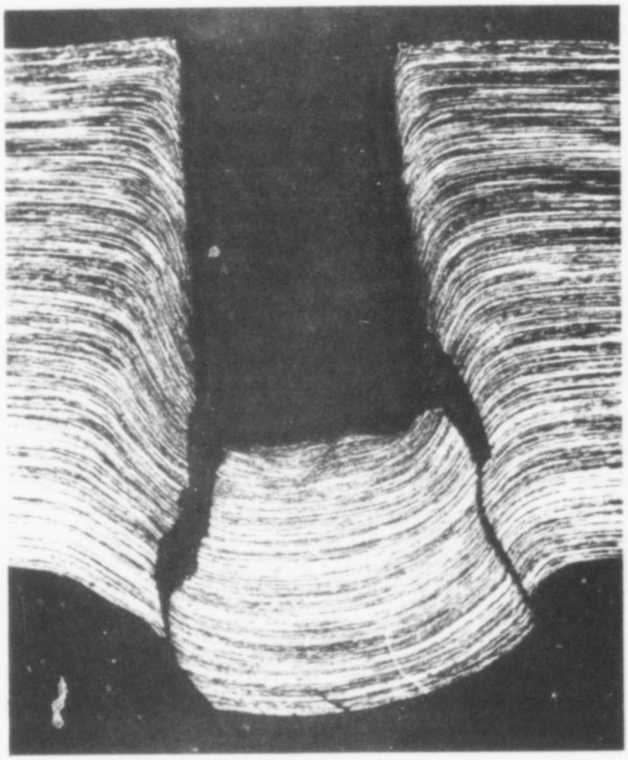

FIG. 1(c) - Plugging.

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