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of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 1346.

The Physics of Armour Penetration.

(Copy No. 18.)

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The Physics of Armour Penetration.

Introduction.

At the request of Mr. H. L. Batten, T.O. D5, for Inspector General, Inspection Board of United Kingdom and Canada, 70 Lyon Street, Ottawa, Ontario, we have undertaken to review some of the recent literature on armour and to abstract information which we consider to be of practical value.

The result is not a treatise on physics of armour but, rather, an attempt to describe in simple terms what actually happens when projectiles strike armour. Like all other phenomena in nature, it is probable that armour penetration behaves according to exact laws. The true laws governing penetration have been approximated, but they are so modified by the varying properties of the materials used that exact prediction of performance is not yet possible.

G. S. Farnham,
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TYPES OF BEHAVIOUR OBSERVED IN ARMOUR.

Body Armour:

Small-calibre projectiles are used against steel helmets and body armour. The energy of the projectile is used up in forming a dome-shaped bulge up to four or more calibres in diameter. It appears that the metal is all stressed in tension. This is due to its flexibility. Tensile test properties therefore determine serviceability for this type of armour. Manganese steel possesses good properties for this type of service. Typical physical properties of manganese steel are:

Elastic limit, p. s. i.	Tensile strength, p. s. i.	Elongation, per cent in 2 inches	Reduction of area, per cent	Brinell hardness
50,000	145,000	65	50	230

Low elastic limit combined with a high tensile strength is required for body armour. A superior product has been developed which is essentially austempered .60 - .80 carbon or low alloy steel. It also has this low elastic limit and long period of plastic deformation.

Indenting:

The laws governing the slow penetration of steel plates have been worked out. The earliest of these was the Brinell equation:

$$H = \frac{P}{\pi \frac{D}{2}\left(D - \sqrt{D^2 - d^2}\right)}$$

H = Brinell hardness number.
P = Load applied in kilograms.
D = Diameter of ball, mm.
d = Diameter of indentation made by ball.

For a given loading force, depth of penetration decreases as hardness becomes greater.

Pressure Required to Continuously Penetrate:

The pressure at which a loaded punch will continuously penetrate a block of ductile metal is known as the pressure of fluidity.[*]

Pressure of fluidity = 2 x Brinell hardness number (Kg/mm^2)

EXAMPLE -

Brinell hardness - 200.
Punch - 1 mm. x 1 mm.

Pressure required to sink punch = P

$$P \times 1mm^2 = 2 \times B.H.N.$$

$$P = 400 \text{ Kg.}$$

This simple equation shows how increasing hardness gives increasing resistance to slow penetration.

Zener[**] has stated that in slow punching an equilibrium of forces is established in the plate. In high speed penetration there is not time for an equilibrium to be set up, and hence pressure of fluidity laws are not applicable.

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Rebound:

If conditions of attack are such that the energy of the shot can be all absorbed elastically, then the shot will rebound. The harder plate is made the greater the amount of energy that can be dissipated elastically.

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* OBSERVATIONS ON THE PRESSURE OF FLUIDITY OF ANNEALED METALS, O'Neill & Greenwood, J.I.M. No. 1, 1932.

** Private communication.

Complete Penetration:

The observed phenomena associated with penetration of armour are classed as: petalling, plugging, spalling, or shattering.

Petalling is the preferred type of penetration. In this case the shot penetrates without dislodging pieces of plate. The word 'petal' refers to the appearance of the edge of the shot-hole.

Plugging occurs when a slug of metal is sheared out of the plate by the shot.

Spalling refers to the dislodging of a disc of metal from the back of the plate. Spalling is generally considered to have disastrous effects on personnel.

Shattering of armouring generally occurs when the projectile energy is far in excess of that needed to defeat the plate.

There is evidence to show that the same plate will petal, plug, or spall, depending upon angle, calibre and velocity of projectile.

PREDICTING RESULTS OF ARMOUR ATTACK.

There have been many attempts to tie together the effect of shot of different calibres and different velocities on plate of varying thickness into one equation. If such an equation were available, then the results of any projectile against any plate could be predicted. Jacob De Marre, in 1886, developed an equation involving mass of shot, velocity, calibre, and thickness of armour. This dimensional-type equation has been modified from time to time. All of these equations assume that the striking energy which defeats the plate is a function of $\frac{MV^2}{\text{Diam. of Shot.}}$

Dimensional-type equations -

Ordnance Board (Eng.)	$W^{\frac{1}{2}}V$	=	$C_1T^{0.715}D^{0.785}$
De Marre	$W^{\frac{1}{2}}V$	=	$C_2T^{0.7}D^{0.75}$
Krupp	$W^{\frac{1}{2}}V$	=	$C_3T^{0.667}D^{0.833}$
Moisson	$W^{\frac{1}{2}}V$	=	$C_4T^{0.667}D^{0.333}$
Thompson	$W^{\frac{1}{2}}V$	=	$LT^{1.5} - MDT^{0.5} + ND$
Stockdale	$W^{\frac{1}{2}}V$	=	$C_5D^{0.5}\,T + C_6D^{1.5}$
Thompson's F value	V	=	$\frac{(T/D)^{\frac{1}{2}}\,F\ \sec.\,\Theta}{(W/D^3)^{\frac{1}{2}}}$

W = Mass of projectile, in pounds.
V = Striking velocity, in feet per sec.
T = Thickness of plate penetrated, in mm.
D = Diameter of shot, in inches.
$L_1 m_1 n_1 c_1 - c_6$ = constants.
Θ = Angle of attack.

Some physicists have been working on the problem of developing a satisfactory equation from other angles. Zener considers the energy wave generated. Beta considers a cone or ring of metal under stress.

It is probable that a perfect equation would include dimensions, wave energy, stress systems, and physical properties of the materials.

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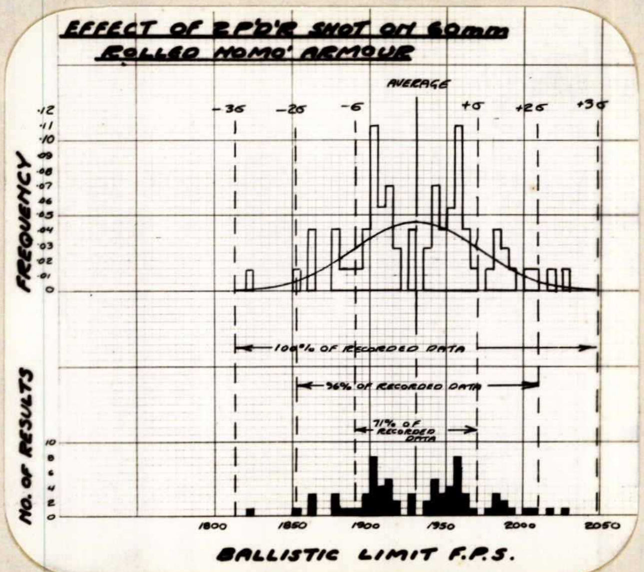
CONDITIONS WHICH MODIFY PENETRATION PHENOMENA.

Variance of Ballistic Limits:

From the foregoing equations one would be led to believe that with a given shot and plate and angle of attack ballistic limits would be constant. Proving ground results show that ballistic limit is variable. Figure 1 shows how the test results were distributed for seventy-three ballistic limit tests on 60-mm. armour using a two-pdr. shot.

Figure 1.



The existing ballistic formulae do not take into account the variations in the properties of shot and plate. For this reason one should not rely too greatly on the De Marre type of equation. A limit of accuracy should be quoted. Average and standard deviation of ballistic tests should be included. Following is a discussion of physical factors that modify ballistic limit.

Shot Properties:

An ideal shot would be hard enough and sufficiently tough to penetrate armour without any distortion in the shot. The nose of the shot is under compression loading. Compressive strength increases with hardness, therefore, armour piercing shot are made as hard as possible at the nose. 600 B.H.N. is a representative nose hardness. The body and base of the shot are subject to bending and torsion impact. Impact strength is obtained by controlling hardness to 300-400 B.H.N. in the cylindrical part of the shot and about 200 B.H.N. at the base.

Soft shot may bend or bulge and stick in the plate. Hard shot may shatter into fragments without doing much damage to the plate.

Industry cannot produce shot which are all exactly alike. A certain amount of variation in shot is normally expected. This variation in shot will cause variation in the phenomena of penetration.

The propellent charge in a gun undoubtedly varies from round to round. Thus, if the velocity of projectile is unknown the variations in results on attack may be partially assumed to be due to variations in the propelling charge.

The performance of the gun may conceivably affect the stability of the shot in its flight.

Armour Plate Properties:

Armour plate is, from the mechanical viewpoint, a non-uniform material. The characteristics of armour which mainly control its ballistic properties are inclusions, microstructure, homogeneity, and hardenability.

Inclusions -

Non-metallic inclusions may be considered as voids in the metal, since they have no strength. They are always present in steel to some extent, but they have the power to make the steel very low in impact strength. It is probable that inclusions are one of the major factors controlling ballistic limit of armour plate. Plastic inclusions are those which are squeezed out into long stringers when the steel is forged or rolled. It is well known that the greater the reduction in thickness the greater is the difference between longitudinal and directional properties. This phenomenon is attributed to elongated inclusions. It can be visualized that the amount of reduction in thickness must be held to a certain minimum in order to prevent this effect. Smaller billets and ingots have been recommended for gun tubes and rolled armour for this reason.

Elongated inclusions have been found in inferior types of armour plate. Refractory inclusions are circular in shape. They may be oxides of aluminium, chromium, silicon, or iron, or compounds of deoxidisers such as zirconium and titanium. Whether they affect the plate properties depends upon their amount and form of distribution. Cast steel if improperly deoxidized may have a network of inclusions about the grain boundaries which makes the steel very weak and brittle. Certain combinations of non-metallic elements will form dispersions of inclus ons which result in low ballistic properties.

Microstructure -

Recent work with the electron microscope has led to the belief that all tempered steel structures consist of dispersions of carbide particles in iron. Tempered martensite, troosite, sorbite, and pearlite therefore differ mainly in the size of the carbide particles. This concept is used in this report.

Armour steel should consist of a uniform dispersion of carbide particles in a steel matrix. It is generally agreed that perfect homogeneity of structure is desired for optimum ballistic properties. Tensile strength and hardness is directly proportional to carbide particle size. Impact strength, reduction of area, and elongation are also mainly dependent on carbide particle size and distribution.

Hardenability -

There is evidence to show that good armour must be capable of being hardened throughout. This means that carbide particle size is approximately the same at the centre as on the outside. Sufficient alloy must be present and/or quenching must be drastic enough to prevent transformation of austenite at elevated temperatures.

Variations in hardenability of steel from heat to heat are to be expected.

PHYSICAL LAWS FOR SHOT PENETRATION ARE MODIFIED BY HARDENABILITY.

Armour Homogeneity -

Cast armour plate is not uniform in structure. There are dendritic areas richer in alloy than the matrix. This results in planes of weakness in the metal. The cast structure is low in impact strength. Rolling tends to break up the structure of the metal and collapse any cavities. Hence rolled armour plate is slightly superior to cast plate. Cast armour must be heated at fairly high temperatures long enough for the alloy to disperse itself uniformly throughout the steel. The more alloy is used, the more difficult it becomes to homogenize the armour. There is therefore both a minimum and a maximum for alloy content.

If quenching is not fast enough, ferrite will be precipitated. The presence of ferrite has been shown to be a characteristic of low quality armour plate.

PHYSICAL LAWS FOR SHOT PENETRATION ARE MODIFIED BY THE HOMOGENEITY OF THE STEEL.

CALCULATING RESULTS OF ARMOUR ATTACK.*

Part 1. - How to calculate effect of change in projectile size, other factors being constant.

$$\frac{W}{DT^2} = K_1$$

W = Mass of projectile, in pounds.
D = Diameter of projectile, in inches.
T = Thickness of plate penetrated, mm.
K_1 = Constant.

The above equation appears to hold for a constant velocity. For example, if we know that a 2 pdr. at 1930 f.p.s. will penetrate 60-mm. armour plate. What thickness of plate would a 75-mm. shot weighing 14 pounds penetrate at

* Following data are abstracted from: D.T.D. Experimental Report No. A.T. 11, NOTES ON THE PENETRATION OF ARMOUR BY A.P. PROJECTILE, by Capt. D. Stockdale, R.A., Issued by Armour Trials Section, Dept. of Tanks Design.

the same velocity?

A. 2-Pdr. = 14-Pdr.

$$\frac{W}{D\,T^2} = \frac{W}{D\,T^2}$$

$$\frac{2}{1.5''\;\;60^2} = \frac{14}{2.95''\;\;T^2{}_2}$$

Thickness penetrated by 14-pound shot:

$$T^2 = \frac{14 \times 1.5 \times 60^2}{2 \times 2.95} = 11640$$

$$T = 108 \text{ mm.}$$

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Part 2. - How to calculate effect of velocity on thickness of armour defeated, other factors being constant.

V = a(T+b), shot dimensions constant.

V = Velocity, in ft./sec.
T = Thickness of penetrated plate, in mm.
a and b = Constants.

Before this formula can be used, the constants a and b must be determined from tests at different velocities.

EXAMPLE -

Given - 30° attack;

velocity, 1700 f.p.s., 10-mm. plate defeated;

velocity, 1500 f.p.s., 8-mm. plate defeated.

Q. What thickness of plate would be defeated by the same shot at 1300 f.p.s. velocity?

A. $1700 = a(10+b) = 10a + ab$

$1500 = a(8+b) = 8a + ab$

$200 = 2a$

$a = 100$

$1700 = 100(10+b) = 1000+100b$

$$b = \frac{1700-1000}{100} = 7$$

∴ Equation is $V = 100\,(T + 7)$

when $V = 1300$

$$T = \frac{V}{100} - 7 = \frac{1300}{100} - 7 = 6 \text{ mm.}$$

This means that within certain known limits the curve depicting velocity and thickness penetrated is a straight line. There are certain critical speeds at which shot will shatter. Above and below these speeds shot perform successfully. Hence the equation is only useful in known ranges.

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Part 3. - How to calculate effect of calibre, other factors being constant.

At a constant velocity, and angle of attack, the thickness of plate holed is proportional to the calibre of the shot. The reason for this lies in the fact that all shot have about the same proportions. Therefore,

$$\frac{D}{T} = K_3$$

D = Diameter of shot.
T = Thickness of plate holed.
K_3 = A constant.

A 3" calibre shot would be expected to penetrate twice the thickness of armour that a 1.5" calibre shot would hole at the same velocity.

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Part 4. - How to calculate effect of influence of the angle of attack, other factors being constant.

It must be pointed out that this equation is only a rough estimate for predicting performance; different types of shot do not behave in a similar manner. The modified De Marre equation as used by the Ordnance Board is

$$\frac{WV^2 \ Cos^2 \ 0}{D^3} = C\left(\frac{T}{D}\right)^{1.43}$$

For a given shot this reduces to

$$T = c \cos^{1.4} 0$$

If 2-pdr. shot defeats 40-mm. plate at 30° with a velocity of 1800 f.p.s., then

$$T = c \cos^{1.4} \theta$$

$$40 = c \; .866^{1.4}$$

$$C = \frac{40}{.515} = 77.6$$

SHOCK PHENOMENA.

The previous equations are based on the idea that the effect of a shot is a function of $\frac{\text{mass x velocity}^2}{\text{area of impact}}$. As long as the energy of the shot is utilized in plastic deformation of the plate the Brinell-type formula applies. When the plate is plugged or petalled the De Marre type equation holds approximately. For pinhole failure the Krupp equation applies more accurately.

A noteworthy example of the failure of these simple types of equations to predict armour performance occurred when 3-in. plate was proofed with 37-mm. shot. It was discovered that some plate satisfactory on the 37-mm. test would shatter or crack when struck obliquely with heavier projectiles at a low velocity. It was necessary to develop a "shock test" to supplement the 37-mm. test. The empirical equations for armour penetration did not successfully predict the effect of heavier projectiles.

It was found that in order to successfully resist heavier projectiles, softer plate was required than for light projectiles.

Let us assume that below a critical energy concentration the energy of the shot is dissipated in local elastic and plastic deformation of the plate. As the critical energy concentration is reached, the type of phenomenon is changed. A 2-pdr. and a 6-pdr. shot compare at 2000 f.p.s., as follows (note the 6-pdr. has only 50 per cent more energy:

2 pdr. | 6 pdr.

$$E_{2pdr} = \frac{\frac{1}{2}M_2V^2}{D_2^2} \qquad E_{6pdr} = \frac{\frac{1}{2}M_6V^2}{D_6^2}$$

$$\text{ratio } \frac{E_{6\,pdr}}{E_{2\,pdr}} = \frac{M_6\,D_2^2}{D_6^2\,M_2} = \frac{6 \times 1.567^2}{2.25^2 \times 2} = \frac{1.48}{1.00}$$

A 2 pdr. at 4000 f.p.s. compares to a 2 pdr. at 2000 f.p.s. as

$$E\,4000 = \frac{\frac{1}{2}MV^2}{D^2} \qquad E\,2000 = \frac{\frac{1}{2}MV^2}{D^2}$$

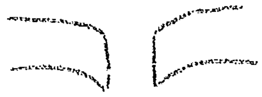
$$\frac{E\,4000}{E\,2000} = \frac{4000^2}{2000^2} = \frac{16}{4} = 4$$

Greater advantage would appear to attach to increasing velocity than to increasing calibre. The attainment of high velocity involves many practical difficulties. As a certain energy concentration per square inch is exceeded, the penetration phenomenon changes its nature. It is assumed that the impact of shot initiates waves of compression and tension in the armour plate. If armour is soft, compression waves are of small order since the majority of the energy is used up in plastic working of the metal.

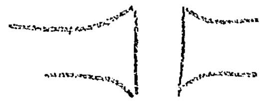
Energy Waves in Plate:

Anyone who has held an iron pipe which was struck a sharp blow has received painfully convincing evidence that energy waves travel in metal as a result of an impact. Bells are so designed that the elastic energy waves induced are converted into sound. Two types of wave motions must be visualized, the plastic wave and the elastic wave. Tuning forks and bells are evidence of elastic waves in metal, since there is no permanent displacement. Practical evidence of the existence of plastic waves is obtained from tension impact tests. In this test a tension specimen is pulled apart by engaging with a high-speed device. Considerable evidence has indicated that the impact strength remains at the same level as impact speed is increased up to a certain point. At this "critical velocity" the energy required to break the specimen drops to a low value and with increasing velocities it remains at this low level. There is then a certain velocity where the nature of the impact load is changed. We may assume that since speed is the variable, energy waves are the interfering phenomena. Other evidence that plastic waves exist is given by marking tension impact specimens uniformly and recording the elongation of each section.

Still further evidence of plastic waves is given by the appearance of the hole when a plate is pierced slowly and at high velocity.



Pierced slowly.



Pierced at high velocity.

Note that the metal is piled up on the side the shot enters.

If energy waves of high enough intensity could be initiated by the shot, the plate would be shattered. Body armour due to its flexibility can easily dissipate energy waves, therefore it can be made quite hard provided, of course, that it has fair plastic deformation properties. As armour becomes heavier and possesses more rigidity and inertia, its capacity to dissipate wave motions does not increase proportionately with its mass. This is the reason that heavy armour must be soft. The low yield allows of plastic deformation before stresses are built up.

The energy of the shot is transformed into plastic work and elastic movement in the plate. One estimate places the fraction of energy dissipated elastically at 20 per cent when near the ballistic limit and plate is one calibre thick. With thicker plate, the elastic absorption of energy decreases markedly.

From the Pressure of Fluidity law, the force required to sink a punch (Kg/mm^2) = twice Brinell hardness number. Resistance to punching, that is, resistance to plastic flow therefore increases with hardness. Under static loading this is a straight line relationship. Under ballistic conditions it can be visualized that at low hardnesses very little energy is absorbed elastically by the plate. Energy is absorbed by plastic flow until the plate is perforated. As plate becomes harder, more and more energy is absorbed elastically until eventually a brittle type of failure results. The ductile type of failure can be explained by empirical equations, Brinell, De Marre, and Pressure of Fluidity law. Erratic behaviour of brittle failures is attributed by Zener to energy waves in the plate.

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Types of Shot and Plate:

The nose of an armour-piercing shot is subject to terrific compression impact. It has been found that under certain conditions a soft steel cap will greatly increase the shot's effectiveness. A supporting ring of soft metal can be visualized as holding the nose of the shot together as it penetrates the plate. Face-hardened plate is used to break up the shot. This type of plate is successfully attacked with hard-nose shot. The application of any furmula to armour penetration phenomena is constructing a mathematical model of reality which, while it may be accurate over a small range, cannot be used for wide interpolation. For the practical student of ballistics it would be of more value to study actual firing test results of a wide range of plate thickness, projectile size, and velocity. Having on hand tabulations of actual ballistic results one may then make a better estimate of the results of attack.

It is obvious that equations for armour performance are modified by the type of plate. Face-hardened, homo-hardened, and homo-machineable armour are compared in other sections of this report. Capped and uncapped shot and cased and uncased shot behave differently also. The discussion of the equations of armour performance is therefore of a general nature only.

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