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“The Manufacture and Efficiency of Armour-Plates.”¹

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It is nearly forty years since armour-plate was introduced as a protection for war-ships. From that time there has been a constant struggle for superiority between projectiles and armour. It may be said that almost equal advances in the manufacture of both plates and projectiles have been made, chiefly owing to the strong competition between British and foreign manufacturers.

MATERIALS.

Iron plates were introduced by the French, and applied to floating-batteries during the period 1854–58. The “*Gloire*,” launched in 1860, was the first sea-going ship to which armour-plates were applied. In the year 1861, the British Government formed a “scientific committee for the purpose,” says Dr. W. Pole² (one of its number), “of investigating generally the application of iron to defensive purposes [in war.” After an extensive series of experiments, the committee decided that “the most suitable material was simple malleable iron.” For many years that material was used, while the thickness of the armour-plates varied. The tough malleable nature possessed by wrought-iron gave it a good place as long as the material of which the projectiles were made had a constant value.

But increased strength of guns, attended with higher projectile-velocities, called for a stronger material than wrought-iron; consequently the introduction of steel armour-plate excited considerable interest. Its first appearance for trial was in 1876, at the Muggiano proving-grounds near Spezia,³ and to Schneider must be attributed the credit of having first manufactured steel armour-plate. A spirit of rivalry was aroused among English

¹ This Paper was read at a meeting of Students on the 14th April, 1893, and has been awarded a Miller Prize, Session 1892–93.

² Minutes of Proceedings Inst. C.E., vol. xeviii. pp. 65, 66.

³ Trans. Inst. N. A., 1891, vol. 32, p. 138.

manufacturers on the advent of the foreign steel-plates, and in a short time Messrs. Cammell and Co. and Messrs. Brown and Co., of Sheffield, the renowned iron-plate makers, converted their plant to suit the manufacture of steel armour-plates. In the year following this important advance in the manufacture of steel plates, a compound armour-plate was introduced by Mr. A. Wilson, and by many it has been considered superior to the solid steel-plate.

A further advance was subsequently made by the introduction of nickel into the solid steel-plates.

MANUFACTURE.

Many methods have been proposed for the manufacture of armour-plates, and if the expense entailed in conducting experiments were not so great, the development of various plans suggested might lead to successful and practical issues. There are three principal methods of manufacture carried on at the present time :

(1) "Wilson's Compound Armour-plate" consists of a soft tenacious wrought-iron plate, united with a hard steel-plate in the ratio of one-third steel to two-thirds iron. The iron-plate is first manufactured so as to fit into an iron mould of the shape of the compound plate required. The space between the iron-plate and the inside of mould is filled with molten steel, which unites with the wrought-iron plate, making the line of contact difficult to discern. The need of a tough back in the compound plate involves the removal of all foreign matter from it, and for this reason the iron-plate is carefully composed of many thin plates of puddled iron. Iron can never be wholly free from impurity, owing to the fact that while it is being manufactured from the "pig" in the puddling process, by the partial extraction of carbon and other impurities, the liquid cinder or slag permeates the mass. Although squeezing the balls at a welding-heat largely effects the removal of the slag and gases, yet it only reduces the films of cinder, leaving the whole mass like a network of slag, the interstices being filled with crystals of iron.

The presence of phosphorus and silicon also—elements difficult of removal—is detrimental to perfect homogeneity and malleability. To what extent phosphorus and silicon diminish the value of the armour-plate can only be understood by considering the influence they exercise over the particles which together

make up the plate. Mr. W. F. Dumfries has given an interesting account of the effects produced in iron-plates by phosphorus and silicon, and points out that these elements diminish the "cohesive attraction between the particles of iron enclosed in the slag," which inclines to produce a crystalline instead of a fibrous structure when the material is cold.¹ Prof. Roberts-Austen² says, "any circumstance which inclines to produce crystallization must affect the malleability." It is therefore clear that the presence of those elements in the plate impairs its powers of resistance.

The iron-plate after manufacture is heated to a high temperature and pressed horizontally into the iron mould already described. The mould and plate are swung into a vertical position and lowered into a pit for convenience of casting. Over the open space in the mould is fitted an iron trough lined with fireclay, through the bottom of which are numerous preforations; so that the steel, which is run into the trough from the ladle, may be as far as possible free from slag when it enters the mould. The trough also causes the molten metal to stream into the mould like water from the rose of a watering-can, diminishing the inrush of air drawn with the falling body of molten metal into the mould, which often causes unsound castings that can never be made good by working the material. The compound body, when sufficiently cool, is removed from the mould and gradually re-heated in a furnace. The mass is then submitted to hydraulic pressure, after which it is passed through the rolling-mill and reduced to the thickness required. The next operation is bending the plate to the curvature of the ship's side, which is done under a powerful hydraulic press. Finally, the plate is machined and drilled.

(2) The second important method of manufacture is that known as the Ellis process. It consists in combining a soft tough iron back with a hard thin steel-plate, by casting a layer of steel between the two. The process is conducted in the following manner:

With the same care as in the method last described, the iron-plate which forms the back of the armour-plate is made a little larger than the requisite finished dimensions. The thin hard steel face-plate of the armour is next made, and when both plates are cold, they are held in a position parallel to one another, with their faces kept a few inches apart by strips bolted to the iron-plate along the sides and bottom. The two plates are next

¹ Proceedings of U.S. Nav. Inst., 13, p. 369.

² "Introduction to the Study of Metallurgy," p. 7.

removed to a heating-furnace, and when the whole mass has been brought to a red heat, it is taken to the casting-pit and fitted in a vertical position, after which the space between the two hot plates is filled with molten steel, causing the three laminæ to unite. The subsequent operations are conducted similarly to the method described in the first case. In conjunction with the manufacture of the Ellis compound plate, Captain Tressider has lately introduced a mild steel back, containing about 2 per cent. of nickel to replace the soft iron.

(3) All-steel armour-plate is made by nearly every armour-plate maker.

Steel armour-plates are classified according to the material alloyed with them. The method of manufacture is, however, practically the same for all solid steel-plates. The principal points of interest in the manufacture are found in tracing the development of each process from the steel-furnace. Carbon chemically combined with iron may be said to be the distinguishing element between wrought-iron and steel; but since this fact was known, it has been proved beyond doubt that the chemical combination of other elements greatly modifies the physical properties of the compound.

The furnaces usually employed for the manufacture of steel for armour-plates are the Bessemer and Siemens-Martin—preferably the latter. Another good furnace, *Fig. 1*, invented by Mr. Radcliffe, of the Woolwich Arsenal, is used with success both in the Royal Arsenal, for the manufacture of ordnance and ammunition, and at the Thames Iron Works, in the production of experimental steel armour-plates. Although these furnaces differ in construction, the object of all of them is the same, namely, the decarburization by oxidation of the “pig” and “scrap,” or the “pig” and “ore,” according to the process employed; and afterwards the addition of a re-carburizing agent, such as ferro-manganese or spiegeleisen, in the quantity corresponding with the required percentage of carbon. When a special mixture is required—for instance an alloy of nickel and steel—care must be taken that a minimum amount of nickel be oxidized; and also that it be added in a liquid condition to the charge at as early a stage in the manufacture as possible, so as to increase the homogeneity of the steel and to diminish the risk of producing “blowholes.” To prevent oxidation in the bath of the furnace, it is necessary to keep a good slag over the molten metal. The recarburizing agents are added to the charge as in the ordinary method. Nickel may also be added in the liquid state to the steel in the furnace,

just before tapping. The amount usually added is 2 to 5 per cent. From the furnace an ingot of steel is run, sufficiently large for the armour-plate required. It is allowed to solidify gradually, to prevent as far as possible internal strain or rupture. A perfectly sound ingot is rarely obtained owing to the formation of "blow-holes" in the steel. Attempts have been made to prevent the occurrence, by mechanically agitating the steel in the furnace, and also whilst in the ladle; but neither plan has been successful in freeing the steel entirely of blow-holes. The ingot is removed to the re-heating furnace, where it is important that the heat be applied to the mass very gradually and maintained at a proper temperature, to prevent internal injury either from unequal heating or over-heating. When the ingot is heated throughout to a bright red heat, it is reduced to the size required under the steam-hammer, or in the rolling-mill.

Fig. 1.

RADCLIFFE STEEL FURNACE.

Although the value of the material is much increased in these operations, yet an ingot with blow-holes in it cannot be made good, however much rolling or hammering it receives; and its value is often diminished by the elongation of these holes into fine tubular threads, forming in many cases the seat of a "through crack" when the plate is subjected to fire. A few months ago the Author observed that an armour-piercing projectile, some time after it was hardened, cracked longitudinally from point to base. When the fracture was revealed, the metal was found to be good with the exception of a long plain narrow streak from end to end, which presented the appearance of a blow-hole drawn out like a thin cord. This is just as liable to exist in armour-plates, and to prove as injurious.

The two principal methods of hardening armour-plates known in England and in America, are respectively the "Tressider" and "Harvey" processes. The former process consists of laying the heated armour-plate below a number of pipes placed horizontally like a grid-iron. The pipes are about $\frac{3}{4}$ inch in diameter, and along the lower side of each are drilled holes about $\frac{1}{8}$ inch in diameter, to allow water ejected from the pipes under pressure to play upon the hot plate. The injurious effects produced by the ordinary method of quenching in a water-bath, due to the irregular abstraction of heat from the surface of the body, owing to the envelope of steam which separates it from the water, are considered to be thus overcome without any reduction in the hardness of the armour-plate.

In the Harvey process, the face of the armour-plate is hardened by cementation. The plate is bedded in sand to about two-thirds of its thickness at the bottom of the furnace. The exposed part is packed closely with charcoal or other carbonaceous matter. The furnace is maintained at a high temperature long enough to allow the steel to absorb the required amount of carbon. The plate is then removed from the furnace and allowed to cool slowly until it reaches a dull red heat, after which it is suddenly chilled, either by sprays of water or by being plunged bodily into cold water.

Neither of these processes can be said to give absolutely

Fig. 2.

CONNING TOWER.

Fig. 3.

CASEMATE.

satisfactory results. The great weakness in all such artificial methods of hardening is, that they are not applicable to armour which has to be curved to the lines of a ship. The cost of conducting the operations is also considerable. Not only has the

plate to be heated repeatedly in the Harvey process, but it has often to be machined all over after the hardening is completed, to remove the irregularities caused by warping. When difficulty is experienced in hardening small flat plates, it will be readily understood how impossible it is to apply such processes of hardening to the forms of armour illustrated in *Figs. 2* and *3*. The former *Fig.* shows the conning-tower for the Spanish cruiser "Infanta Maria Teresa;" and *Fig. 3* is a view of the casemate for the protection of a 6-inch gun on H.M.S. "Hawk."

EFFICIENCY OF ARMOUR-PLATES.

The material of which an armour-plate is composed should have a resistance to penetration equivalent at least to the total energy of the projectile at the instant it strikes. The difficulty of obtaining such material increases daily, owing to recent improvements in the manufacture of forged-steel projectiles, and the increased velocities at which they strike the plates. When wrought-iron plates were used, their combined tenacity and toughness proved sufficient to resist the best projectiles then produced; and, although perforation was sometimes effected, the damage done to the plate was local.

Steel armour-plates, with their increased resisting-properties, have done much to oppose the penetration of the forged chrome-steel projectiles, and perforation has in many instances been checked by reason of the plate gradually absorbing the energy of the shot before it has completed its passage through it. This has, however, been not infrequently attended by cracks extending throughout the entire length of the plate. It was with a view to combine the qualities possessed by the steel and the iron plates that compound armour was introduced. The steel plate, with its high resistance to surface penetration, coupled with a tough malleable backing of wrought-iron, gave promise of being free from the weakness of former plates. If by repeated blows, under exceptionally severe trial, the hard face of the plate be penetrated, surface-cracks may appear, but the tendency to "through-cracking"—the inherent vice of all-steel armour-plate—is not great, because of the malleable body to which the hard plate is united. Compound plates have been condemned on account of a possible danger of the steel face becoming detached in fragments from the iron plate whilst under fire, thus exposing a surface totally incapable of resisting the projectile; but the union which exists between the two materials

has stood the most severe attacks of specially-hardened forged-steel projectiles, without much sign of such weakness.

Fig. 4 illustrates the front of a compound steel-faced armour-plate, tested by Messrs. Cammell and Company, after being fired at five times on the 27th of August, 1891. Although the striking-velocity of the 6-inch forged-steel shot was nearly 2,000 feet per second, it will be seen that the plate was hardly damaged, and it succeeded in breaking up and destroying every projectile hurled against it. The bulges in the rear of the plate were hardly perceptible.

Another compound plate, 8 feet by 6 feet by 10 inches thick, made by Messrs. Brown and Company of Sheffield, and surface-hardened by the Tressider process, was privately tested by

Fig. 4.

FRONT.

Government officials at Sheffield, on 4th August, 1892. *Fig. 5*¹ is a front view of the armour-plate after resisting and breaking up into many fragments the five 6-inch Holtzer Forged Steel projectiles fired at it. The weight of each projectile was about 100 lbs.; the average striking-velocity about 1,950 feet per second, and the energy nearly 2,655 foot-tons. A few fine cracks caused by each shot appeared in the plate, but they were so slight that they could only be seen by close examination. The maximum and minimum penetrations of the projectiles were 8 inches and 1·09 inch respectively, while the bulges on the back were very

¹ Reproduced from a photograph by the kind permission of the Editor of the *Engineer*.

Fig. 5

FRONT.

Figs. 6.

FRONT.

BACK.

small. On the whole the result is remarkably good, and further demonstrates that the united plates are capable of remaining intact even when exposed to the attack of the best projectiles.

Messrs. Cammell and Company have recently supplied to the British Admiralty 3 all-steel armour-plates for test. The results obtained were remarkably good: the first plate, of the same size as the compound plates referred to, was tested on board the "Nettle," on the 9th of December, 1891. The Holtzer projectiles fired at it were all stopped. One remained in the plate, the second rebounded and broke up, the third rebounded apparently uninjured. Two Palliser shells broke and stuck in the plate. There was not a single crack in the plate, either at the back or front, although small fissures and bulges were made behind the points of the impact. On the 12th of January, 1892, three Holtzer forged-steel projectiles fired at the second plate, *Figs. 6*, were all broken, and their penetration was less than that attained in the December trials, though one of the Palliser chilled cast-iron shots caused a through-crack. The third plate, *Fig. 7*,¹ was tested on the 3rd of May, under precisely similar conditions, and stopped all the projectiles without slightest indication of cracking either at the back or front. The two Palliser shells as usual broke up, but in so doing they enlarged the holes to 8 inches in diameter. The back of the plate was bulged, but no fissure was made.

On the 1st of November, 1892, a solid steel plate, made by Messrs. Vickers, of Sheffield, and hardened by the Harvey process, was tested on board the "Nettle," at Portsmouth.

*Fig. 8*¹ is prepared from a photograph of the plate after being subjected to the same trial as those already referred to. The result is one of the best yet obtained. Another Harvey plate, *Fig. 9*¹, made of nickel steel by the Bethlehem Company, was tested on the 23rd July, 1892, at Indian Head, U.S. In this

Fig. 7.

FRONT.

¹ Reproduced from a photograph by the kind permission of the Editor of the *Engineer*.

trial, five 8-inch Holtzer forged-steel projectiles were used, each weighing 250 lbs., and having a velocity of 1,700 feet per second. Three of the projectiles broke after effecting slight penetration; the other two penetrated more deeply and rebounded, one of them causing a through-crack. This and the previous test show that great improvement has been made in the manufacture of the Harvey plate; but the difficulty referred to is experienced when

Fig. 8.

FRONT.

this process of hardening is applied to curved armour. In resisting chilled shot, or any inferior projectile, the plate is greatly racked in consequence of the wedge-like action produced by the shot. The holes made in the plate by these shots are usually from one-third to one-quarter larger than their diameter, whereas a modern forged-steel shot, which does not up-set, makes a hole equal to its diameter only. Owing to this racking effect, steel armour-plate of the finest quality is said to be broken and peeled

off a ship's side by the blows of inferior shot which may be quite unable to pierce it; while such projectiles produce scarcely any effect upon compound armour, as they are simply pulverised against its hard face, without being able to make any practical impression, the indentations being in most cases from 1 inch to $1\frac{1}{2}$ inch deep.

It will be readily understood that great difficulty is experienced

Fig. 9.

FRONT.

in estimating a plate's power of resistance, otherwise than by trial. If it be remembered that the total energy of a shot at the instant it strikes may be distributed in effecting its deformation or wreck, while it imparts to the plate a shock which affects the mass, probably accompanied with slight penetration, radial cracking, bulging at the rear, severing part of the backing, and racking the entire structure; the question may be asked, is it possible to ascertain how much energy has been spent on one

effect of the blow more than on any other? Repeated attempts have been made to formulate rules for the determination of armour-plate efficiency, but, as far as the writer is aware, the best formulas used in this or in foreign countries are either empirical or deduced from the energy expression $\frac{W V^2}{2g}$. The formulas generally employed in England at the present time for the determination of the power of resistance of armour-plate, are that of Fairbairn and that known as "Maitland's formula of 1880."

The former is

$$\frac{W V^2}{2g} = \pi D t^2 K,$$

and gives the energy of a shot in foot-tons at the striking instant.

By transposition,
$$t = v \sqrt{\frac{W}{2g \pi D K}},$$

where t is the thickness of the plate in inches,

W „ weight of shot as a fraction of a ton,

V „ velocity of shot at the striking-instant in feet per second,

D „ diameter of shot in inches,

and K „ a constant determined from experience,

"Maitland's formula of 1880," for all velocities over 700 feet per second, is

$$t = \frac{V}{608 \cdot 3} \sqrt{\frac{W}{D}} - 0 \cdot 14 D.$$

Captain Orde Brown has introduced a ready method for calculating the extreme thickness of iron plate which can be perforated by shot of ordinary figure, by the formula

$$t = \frac{V D}{1,000}.$$

This rule, says Captain Orde Brown, applies to projectiles in which $\frac{W}{D^3}$ approaches 0·4, fired with velocities less than 2,000 feet per second. If applied to projectiles of which the ratio $\frac{W}{D^3}$ is large, as in the 10-inch and 13·5-inch breech-loading guns,

where it reaches 0·5, or to velocities much exceeding 2,000 feet per second, a considerable error arises.

The Gâvre formula, commonly used in France, is

$$P V^2 = a 1600^2 t_1^{1.4},$$

where P is the weight of projectile in kilograms,

V „ velocity of projectile in metres,

a „ calibre of gun in decimetres,

and t_1 „ thickness of plate in decimetres.

This formula has been modified with good results by Mr. J. de Marre, thus :

$$P V^2 = \lambda a^{1.5} 1280^2 t_1^{1.3},$$

where the symbols have the same values as in the Gâvre formula, and λ is a function of the quality of both projectile and plate.

Although the English expressions give approximately the same results, they differ from the foreign formulas at velocities less than and exceeding 1,580 feet per second, as shown in the Table following, calculated for a 6-inch 100-lb. projectile.¹

Formula.	Perforation through wrought-iron, striking at		
	1,000 feet.	1,580 feet.	2,400 feet.
	Inches.	Inches.	Inches.
Fairbairn (English)	5·92	9·88	15·26
Maitland „	5·87	9·72	15·26
J. de Marre (French)	5·01	10·13	19·25
Krupp (German)	4·94	9·82	18·39

The foreign formulas here employed are those communicated by Lieutenant Perry, U.S. Artillery, viz. :—

$$\text{De Marre's} \quad . \quad . \quad . \quad . \quad t^{0.65} = \frac{W^{\frac{1}{2}} V}{\log^{-1} \cdot 2 \cdot 9616 D^{\frac{1}{3}}};$$

$$\text{Krupp's} \quad . \quad . \quad . \quad . \quad t = \frac{W V^2}{\log^{-1} \cdot 5 \cdot 7776 D^{\frac{2}{3}}};$$

where t is the thickness of wrought-iron perforated, in inches,

W „ weight of projectile in lbs.,

V „ striking velocity in feet per second,

and D „ diameter or calibre in inches.

¹ The Author is indebted to Captain Orde Brown for these results.

With a view to test these formulas at high velocities, the Ordnance Committee, on the 20th July, 1892, fired a 6-inch Holtzer forged-steel projectile at a wrought-iron target 17 inches thick, with a striking-velocity of 2,378 feet per second. It would appear from the result, that Krupp's formula is the most accurate for high velocities. In this connection, it may be of interest to note a rough guide given by Captain Orde Brown,¹ as to the structural strength of projectiles and the limits to their possible perforation:

1. Common cast-iron shells will perforate and carry fire through a wrought-iron plate half a calibre thick. 2. Armour-piercing steel common and Palliser shells will perforate and carry fire through ordinary steel or steel-faced armour one calibre thick. 3. Forged-steel projectiles easily pass through wrought-iron plates two calibres thick.

In considering the resistance offered by armour-plates to projectiles carrying high explosives, it is found from experience that hard armour which breaks shells on impact, before they can penetrate deeply, is the most suitable for use in warfare.

The Paper is accompanied by photographs, from which the *Figs.* in the text have been prepared.

¹ "Armour and its Attack by Artillery," Supplement to Part II, p. 131.