ON EROSION OF GUNS.

BY

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I. Introduction.

In modern guns of large caliber, firing heavy projectiles at high muzzle velocities we observe, from the examination of gutta-percha impressions, after several rounds are fired, fine fissures on the surface of bore at the vicinity of the forcing cone. Further firings render these small cracks wider and deeper, extending throughout the length of the bore; finally they enlarge the diameter of bore, particularly at the beginning of the rifling, so that the centering cone for projectiles approaches nearer and nearer the muzzle of the gun. This increase in diameter of bore, whatever its cause may be, is generally called the erosion of guns. The enlarged bore increases the volume of the powder chamber and results in fall of muzzle velocity, and irregularity in centering during the travel along the barrel causes gyroscopic motion of projectiles during flight. Thus the reduced muzzle velocity and instability of projectiles during flight put the gun out of service through inaccuracy of fire. The number of rounds which can be fired with sufficient accuracy we call "life" of gun; it depends much upon caliber and the maximum pressure at firing. An empirical formula¹⁾ is proposed to calculate this life of gun, thus

$$L = \frac{2.5 \times 10^7}{v^2 d (d-2) P^{1.7}}$$

1) The life and power of heavy ordnance. Eng. Vol. 88, 1909, p. 123.

in which L is life in equivalent full charge rounds, v is muzzle velocity in thousands of ft. sec., d is caliber in inches, P is maximum pressure tons per sq. inch. For large caliber guns, in general, the life is estimated at about 150 rounds while in moderate caliber guns about 700 rounds or more¹⁾. Many theories have been published in connection with gun erosion²⁾, but the author is not very well satisfied with the explanations they offer.

1) F. Cwick:—Ueber die Frage der Lebensdauer grosskalibriger Rohre. Mitteilungen ü. Gegenstände d. Art. und Genie-Wesens, 1908, p. 124.

A. Schweeger:—Lebensdauer grosskalibriger Geschützrohre. *ibid*, 1909, p. 349.

J. Castner:—Ueber die Rohrausnützung und die Lebensdauer schwerer Geschützrohre. Stahl u. Eisen, 30 Jahr. Nr. 21, 1910, p. 884.

P. Siwy:—Ueber die Ursachen der schnellen Abnutzung grosser Geschütze. Dinglers polytech. Journal, 1907, Heft 13, p. 197.

Guido Sansoni:—Initial velocity as affected by erosion. Jour. of U.S. Art., 1910, p. 275.

2) V. Recchi:—Die modernen Kriegspulver und deren Einwirkung auf Gewehräufe und Geschützrohre, Zeit. für d. gesamte Schiess- und Spreng., 1 Jahr. 1906, p. 285.

Streffleurs militärische Zeit., Jan. 1912, p. 168.

H. E. Yarnell:—Gun erosion, Jour. American Socie. Naval Eng., Vol. XXII, No. 2, May 1910. Jour. U.S. Art., 1910, p. 181.

F. Abel:—On the erosion of gun barrels by powder products. Jour. Iron and Steel Inst. 1686, No. 2, p. 465.

F. Abel:—Action of the projectile and of the explosives on the tubes of steel guns, *ibid*. 1898, No. 2, p. 241.

Ausbrennen der Geschütze beim Schnellfeuer. Kriegstech. Zeit., 1906, p. 259.

Ausbrennen im Ladungsraum der langen Kanonen schweren Kalibers in den Vereinigten Staaten. Zeit. Schiess- u. Spreng., 1907, p. 211.

P. Siwy:—Die Abnutzung der Geschütze und deren Ursachen. *ibid*, 1908, p. 42. 1910, p. 331,

P. Charbonnier:—Balistique Interieure. O. Doin, Paris, p. 105.

C. Cranz:—Lehrbuch der Ballistik, III Bd., p. 163.

Lanfroy:—Sur la cause des érosion dans l'ames des bouches a feu. Mémorial de l'artillerie de la marine, T. XIII, 1885.

Vieille:—Etude sur les phénomènes d'érosion produits par les explosifs. Mémorial des Poudres et Salpêtres, T. 11, 1901, p. 157.

Osmond:—Note sur la trempe superficielle de l'acier soumis a l'action des explosifs. *ibid*. T. 11, 1901, p. 11.

Gun erosion, Jour. U.S. Art., 1909, Vol. 31, p. 336.

P. R. Alger:—Gun erosion, *ibid*, 1910, Vol. 34, p. 285.

P. R. Alger:—Erosion and ballistics. Proc. U.S. Naval Inst., Dec. 1910.

H. J. Jones:—The erosion of gun tubes and heat phenomena in the bore of a gun. The Eng., March, 24, 1911.

H. Peloux:—The Tschernoff theory of erosion. Jour. U.S. Art., Vol. 41, 1914, p. 344.

H. Fay:—Erosion of guns. *ibid*. Vol. 47, 1917, p. 392.

H. M. Howe:—The erosion of guns. Bulletin of the American Inst. of Min. Eng., No. 134, 1918, p. 355.

H. C. H. Carpenter:—Gun erosion. Eng., June, 1918, p. 640.

The chemical erosion theory is based on the fact that modern smokeless powder, containing a large quantity of nitrogen, produces by combustion nitrogen mono-oxide gas which may corrode the surface of bore. The surface hardening and the carburisation of the surface of bore by carbon or some compound, produced by incomplete combustion of charge, is proved by metallographical study on specimens taken from eroded gun barrels, and the formation of martensite is generally recognized. As the hardened thin layer of martensitic structure formed on the surface of bore is very brittle the mechanical action of high pressure gas or the temperature stress at firing, and also the rubbing of the projectile, will cause numerous fine cracks; this action is considered to be the first step of gun erosion. Erosion caused by pure mechanical action of the gas combined with heating, is variously explained as follows:— 1) The leakage of high pressure gas carrying unburned particles of the powder charge and particles of the metals detached by friction between the driving band of the projectile and the surface of bore eats away the material of gun barrel. 2) The friction between the driving band and surface of bore itself wears off the material so that the diameter of bore is enlarged. 3) By the vortex motion of gas streaming at enormous velocity, and charged with unburned powder, the skin of the material is scraped, especially at the front part of the powder chamber where the forcing cone (front cone of the powder chamber) causes acceleration of gas stream by the reduction of the cross section of the bore. (Charbonnier). 4) The temperature of the gas being over 2500°C , the gas stream melts and scratches off a thin layer of metal from the surface of the bore. 5) By the thermal expansion and contraction of the gun barrel due to firing (i.e. the temperature stress) and the stress caused by the gaseous pressure, a thin cylindrical

layer on the inner surface of the barrel is stretched beyond the elastic limit and fine fissures are produced.

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It is evident from these suggested explanations, though the causes of gun erosion are not yet fully explained, that the temperature of combustion of smokeless powder plays a vital part in the erosion of guns. But there has been no decisive experiment conducted to determine the temperature¹⁾ of combustion of explosives and to find out the temperature of gun barrels at the instant of firing. The combustion temperature, in general, must be calculated under some assumptions based on the results of calorimetric measurement and is computed to be about 3200°C and 2500°C for nitroglycerine and nitrocellulose powder respectively.

The maximum temperature of the surface of bore has hitherto only been estimated by the metallographical method. According to H. M. Howe²⁾ the surface is heated to about 1250°C “at the instant of highest heating” and martensitic structure is observed, a proof that the surface has been heated to 750°C at least. The formation of martensitic structure and moreover the melting of a part of the surface of bore is recognized by many investigators³⁾,

1) Wuich:—Ueber die bestimmung der Verbrennungstemperatur von Explosivstoffen. Mit. Gegen. Art. Genie. 1891, p. 67.

Blittersdorff:—Der Arbeitsverlust beim Schuss durch Wärmeabgabe an die Waffe und die Ermittlung. Kriegstech. Zeit., 1903, p. 58.

Hirsch:—Untersuchung über die beim Schuss eintretenden Verluste an Arbeit der Pulvergase. ibid., 1903, p. 361.

P. St. Robert:—Principes de thermodynamique. Turin. 1870, p. 266.

Sir A. Noble:—Researches on explosives Part, I and II. Heat action of explosives. Artillery and Explosives. London, 1906.

J. Tobell:—Ueber die Ursachen der Lauferwärmung beim Feuern, Mit. Gegen. Art. Genie., 1888, p. 551.

A. Indra:—Neue ballistische Theorien. Pola, 1893.

Bertrand et Laroche:—Température dans les armes par le tir. Mémorial des poudres et salpêtres, T. 6, 1893, p. 224.

Billardon:—Température développée dans les armes par le tir. ibid. T. 9, 1898, p. 61.

T. Yoshida:—Strength and temperature of gun barrels. Kaheigakkaisi, Vol. I, p. 127.

2) H. M. Howe:—l. c.

3) Vieille, H. Fay, H. Howe, C. H. Carpenter and etc.†.

while Roberts-Austen¹⁾ states that “the result of a thorough examination proves that the action of the explosives has, so far as the mass of the tube is concerned, been purely mechanical. The particles of steel have been simply eroded, and there is no evidence of fusion or of the formation of martensite.”

Several means²⁾ have been attempted to overcome the erosion troubles. Lowering the combustion temperature by adding a certain quantity of carbon or graphite to the powder charge seems to be successful; erosion is also diminished by coating after each round with graphite or grease, so as to decrease the friction between the surface of bore and the driving band of the projectile. In this case we can conceive that not only is the friction reduced but the heating of the bore is retarded and prevented by a thin coat of less conductivity. Another means is the improvement of the form of the forcing cone and the driving band of projectiles so as to prevent the leakage of gas at the beginning of the rifling, where the erosion is most serious. The experiment³⁾ recently made in the United States to get rid of the erosion troubles seems to be very satisfactory, but the details are not reported.

II. Resisting power against gun erosion of various materials.

The erosive effects of the combustion gases of modern nitro-cellulose and cordite powders upon the various materials employed as gun barrels are not yet clearly understood, owing to the difficulties of carrying out such extensive experiments with sufficient number of

1) Roberts-Austen :—The action of the projectile and of the explosives on the tube of steel guns. Jour. Iron and Steel Inst., 1898, No. 2, p. 235.

2) Mommi :—Über den Zusatz von Kohle zu Nitrozellulose-Nitroglyzerin Pulvern. Zeit. Gesamte Schiess- u. Spreng., 1906, p. 305.

E. Bravetta :—Ausbrennungen in Geschützrohren und Mittel zu ihrer Bekämpfung. ibid., 1909, p. 341.

3) H. M. Howe :—l. c.

guns of the same size and made of the various materials to be tested. The only possible means of experimenting on gun erosion on a small scale is the so called bomb test employed by Sir A. Noble, Vieille and others. The result of these experiments as A. Noble¹⁾ has remarked does not, however, agree with experience of actual gun erosion, the resisting power of materials in the former case depending only on the temperatures of melting. The erosion is measured in the bomb test by letting the gas escape through a vent in a plug made of the material to be tested and measuring the increase of volume of the vent. The plug is inserted in a bomb in which a certain amount of the charge is ignited. From Vieille's experiments along these lines we can compute the following table.

TABLE I.

Materials	C	Si	Mn	W	Cr	Ni	Max. pressure in kg./cm ²	Erosion
Swedish iron	—	—	—	—	—	—	2602	75.0
Soft steel	—	—	—	—	—	—	2407	78.7
Gun steel	0.1	—	—	—	—	—	2509	84.5
Chrom steel	0.12	—	—	—	2.0	—	2500	75.5
” ”	0.4	—	—	—	2.0	—	2504	83.8
” ”	0.5	0.27	0.23	—	2.5	—	2430	88.0
Nickel-chrom steel	0.35	—	—	—	1.0	2.0	2625	83.97
Nickel-chrom steel	0.35	—	—	—	2.0	4.0	2504	89.5
Nickel steel	0.259	—	0.43	—	0.59	13-14	2375	106.7
” ”	0.255	—	0.44	—	—	24.4	2430	107.1
” ”	0.070	—	0.285	—	—	26.64	2453	116.9
” ”	0.104	—	0.388	—	—	43.44	2485	134.9
Tungsten steel	0.55	0.20	0.42	2.9	—	—	2333	95.1
Bronze	—	—	—	—	—	—	2546	278.8
Brass	—	—	—	—	—	—	2578	326.0

1) A. Noble:—A sketch of the history of propellants. Trans. Inst. Eng. and Ship. in Scotland, Vol. 52, 1909, p. 274.

In these experiments Vieille explains that the resisting power of the materials against erosion is almost proportional to the temperature of melting.

The erosion effected by actual firing tests, though the full details are not published, does not agree with these experimental results obtained by Vieille. Erosion tests of Japanese infantry rifle barrels made of special steel and also of low carbon steel were carried out, with the result that the former has better resisting power against erosion than the latter with the higher melting point. It is noticeable again that the accuracy life of the Austrian bronze gun is not reached after thousands of rounds, notwithstanding the low melting point of bronze. According to A. Reuter¹⁾, an Austrian 8 cm field gun model 1905, of Uchatius bronze, can be fired with full charge 2856 rounds, without much reducing the accuracy of fire, and some of them have endured as many as 4000 rounds. The life of these guns is almost equal to what we can expect of steel gun barrels while the wear of metal by friction produced by the projectile during the travel through the bore must be far greater than in the case of steel guns.

III. Friction in the bore.

The friction between the driving band and the surface of bore undoubtedly plays a rôle in gun erosion, in a two fold way; it directly wears the skin of the material and at the same time the surface of bore is heated by the frictional resistance. The friction due to the pressure caused by the diametral difference between the driving band and the bore acts on the surface of the lands and grooves. The friction due to the twisting angle of rifling acts

1) Reuter:—Verhalten der Schmiedbronze als Rohrmaterial bei den Feldgeschützen der k. u. k. Feldartillerie. Mit. Gegen. Art. Genie., 1908, p. 349.

of cause on the driving side of the rifling and depends on the magnitude of the normal force acting on the driving side required to rotate the projectile. The normal force on the surfaces of lands and grooves is proportional to the diametral difference, so that it must be greatest at the beginning of the rifling and less as the projectile approaches the muzzle of gun, owing to the wear of materials.

The radial expansion of the diameter of bore, on the other hand, due to the internal gaseous pressure, reduces this normal force on the lands and grooves, so that friction due to the diametral difference becomes a minimum when the gaseous pressure is a maximum. On the contrary the maximum of the friction on the driving side of the rifling occurs when the gaseous pressure is a maximum, the rotational acceleration being proportional to the gaseous pressure. The author¹⁾ has studied the radial compressive resistance of a rifle bullet and loss of muzzle velocity due to the frictional resistance in the bore of the Japanese infantry rifle.

The bullets were fired from the barrels with different angles of twist, and one of the barrels had parallel grooves of rifling. The muzzle velocity was measured by a special instrument devised by the author and the mean radial stress on the coating of the bullet due to the diametral difference was observed to be about 303 kg. This stress must of course be much greater in the case of large caliber guns. If $2r_1$ be the caliber (measured on the land of the rifling), r_2 the external radius of the inner tube, E the modulus of elasticity and p_2 the pressure at rest due to shrinkage or wire winding acting on the external surface of the inner tube, we have the radial compression of bore at rest

1) M. Ôkôchi:—On the resistance of rifling of small arms. Jour. Socie. Mech. Eng. Tokyo. Vol. XVIII, No. 37, 1915.

$$\epsilon = \frac{-2r_2^2}{E(r_2^2 - r_1^2)} p_2 \dots \dots \dots (1)$$

And when the internal pressure P_1 acts, the increase of diameter of bore is expressed by

$$e = \frac{(P_1 - P_2)r_2^2}{E(r_2^2 - r_1^2)} \left(1 + \frac{1}{m}\right) + \frac{P_1 r_1^2 - P_2 r_2^2}{E(r_2^2 - r_1^2)} \left(1 - \frac{1}{m}\right) + \frac{2r_2^2}{E(r_2^2 - r_1^2)} p_2 \dots \dots (2),$$

where P_2 is the external pressure for the inner tube and $\frac{1}{m}$ is Poisson's constant. Now if D_a be the external diameter of the driving band and t the depth of groove we have the following relation.

$$D_a = 2r_1(1 + e) + 2t + f \dots \dots \dots (3),$$

in which f is the diametral difference to prevent the leakage of combustion gas. Hence the radial stress acting on the bottom of the grooves of rifling depends on the magnitude of f ; it is generally chosen between 1.5 to 3 mm, according to the caliber of guns. The pressure on the lands of rifling due to the diametral difference is naturally much higher than that exerted on the bottom of the grooves especially at the beginning of the rifling, where the metal of the driving band has to be cut away by the pushing force of the projectile urged on by the gaseous pressure; but it must be far reduced when the band is deformed and the contact surface is worn down by the enormous friction involved.

Fig. 1.

Next we shall consider the friction on the driving side due to the twist of rifling. This problem was first studied analytically by A. Noble¹⁾, the study has been followed by several experiments. At the cross section of the rifled part as shown in Fig. 1,

1) Andrew Noble :—Artillery and explosives. London, 1906, p. 42, p. 87 and p. 385.

we have N for the resultant normal force, considering the curvature of the driving side¹⁾

$$N = \frac{\left(\frac{\rho}{r}\right)^2 [P \tan \theta + M v^2 f''(x)]}{\frac{1}{\sqrt{\frac{4r^2 r_1^2}{4r^2 r_2^2 - (r^2 + r_2^2 - r_1^2)} + Z_g \tan^2 \theta}} - \mu \sin \theta} \dots\dots\dots(4),$$

in which, ρ and M are the radius of gyration and mass of the projectile respectively, P the gaseous pressure acting on the base of projectile, v the linear velocity, θ the angle of twist, μ the coefficient of friction, and $f''(x)$ the second derived function of curve of rifling. The maximum value of N calculated for the 35.5 cm gun is about 187 tons and the intensity of the normal force on the driving side is about 800 kg/cm² at the instant of maximum pressure attained.

IV. Fine fissures on the surface of bore.

By examining specimens taken from eroded steel gun barrels or by gutta-percha impressions obtained directly from such barrels we always find numerous fine cracks particularly in the vicinity of the origin of rifling, as is shown in the annexed plate. These cracks are considered as the first step of gun erosion. They are enlarged and deepened by successive firing, and then the metal is torn away in lamellar form by the friction of the driving band or by the high pressure gas stream, so that the diameter of bore is gradually increased. To this effect Tschernoff²⁾ may be quoted:—
The first evidences of erosion are manifested in the appearance of dull spots upon the brilliant surface of the bore, principally in the

1) Saburo Takeda:—Theory of rifling (lithograph). Tokyo, 1902, pp. 40–51.
2) H. Peloux:—l. c.

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upper part of the chamber, in the vicinity of the centering cone and cone itself at the origin of rifling. Examination of gutta-percha impressions shows that these spots are made up of net-works of small cracks, extremely fine and very shallow. As a rule, the meshes of these nets are not closed in the incipient stage, but as the firing is continued, the isolated cracks extend, joining the neighbouring ones and forming a net-work of continuous meshes."

On the land of rifling we find generally many transverse cracks which are almost perpendicullar to the gun axis and very few parallel to it, while at the bottom of the grooves most cracks are parallel to the gun axis. At the root of the driving side of the rifling a deep and wide longitudinal crack is sometimes found; it is produced by the normal force on the driving side, which we have already discussed. The increase of cracks in depth and width with successive firing is variously explained as follows: 1) By the thermal expansion and contraction of the gun barrel. 2) By the eating effect of foreign matter, such as particles of copper of driving band and unburned powder grains which act as wedges to widen the fissure. 3) By the leakage of high temperature gas mostly through longitudinal cracks; as in the case of the bomb test, melting of the metal along the cracks is to be expected. 4) By the friction of the driving band, i.e. shearing stress on the surface of bore, by which the transverse cracks are enlarged. 5) By the breaking off of the sharp edges of the cracks due to the compression of driving band.

These are causes of increase and extension of the cracks, but the reason for first occurence of the fine fissures on the brilliant surface of the bore is left still untouched; we shall consider it later.

V. Thermal phenomena in the bore of guns.

Whatever the causes of gun erosion all investigators agree that we can minimise it by reducing the temperature of combustion of the powder charge; thus the thermal phenomena in the bore of guns form a very important problem in gun erosion. We will consider now the state of bore when the projectile has travelled x cm in t seconds after the ignition of the powder charge. The base of shell at loading position is at B , and we assume it has traversed as far as B' , A being the base of powder chamber (see Fig. 2).

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Fig. 2.

The gaseous pressure at this instant is not uniformly distributed over the total space occupied by the combustion gas and we can not treat it as a statical pressure; it is generally higher at the base of the powder chamber, the pressure on the cylindrical surface being comparatively low owing to the oscillation or longitudinal waves of high pressure gas. The temperature and density of the gas is not, therefore, uniform throughout the space between the bases of the chamber and projectile, and the unburned charge still remains in the chamber. Let us assume, however, for the sake of simplicity, that the charge is completely burned and the temperature of gas is uniform, varying only as the time; then we can express the heat quantity Q of the gas, if θ_1 be temperature, c_1

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specific heat, and ρ_1 density of the gas

$$Q = c_1 \rho_1 v_1 \theta_1 \dots \dots \dots (5),$$

where v_1 is the volume of the space between A and B' .

The large part of this heat quantity changes to kinetic energy of projectile; a part escapes from the muzzle as hot gas, while a part is transmitted through the gun wall. Now consider the quantity of heat δQ used to heat gun wall of unit length in time δt ; r_1 is the internal radius of bore which is supposed to be smooth, i.e. without rifling groove; we have

$$\delta Q = 2\pi r_1 h (\theta_1 - \theta_0) \delta t,$$

where h is surface conductivity of the gun wall and θ_0 is its initial temperature. If we assume that during the time δt there is no flow of heat through the gun wall, then the temperature of a cylinder of thickness dr on the surface of bore at the end of δt is expressed by

$$\theta = \frac{2\pi r_1 h (\theta_1 - \theta_0) \delta t}{\rho_0 c_0 \pi [(r_1 + dr)^2 - r_1^2]} = \frac{h (\theta_1 - \theta_0)}{\rho_0 c_0} \frac{\delta t}{dr} \dots \dots \dots (6),$$

in which ρ_0 and c_0 are the density and specific heat respectively of the material of gun wall. The conduction of heat through gun wall now takes place. Imagine, again, another cylinder of thickness dr . The internal radius and external radius being $r + dr$ and $r + 2dr$ respectively, and the temperature θ at the internal surface being expressed by (6), the temperature of the external surface will be

$$\theta + \frac{\partial \theta}{\partial r} dr$$

and the quantity of heat transmitted through a surface of unit length on the internal surface, k being the thermal conductivity, will be expressed by

$$\frac{\partial Q}{\partial t} = -2\pi(r+dr)k \frac{\partial \theta}{\partial r}$$

and the quantity of heat flowing through the outer side of the thin cylinder will be

$$\frac{\partial Q}{\partial t} = -2\pi(r+2dr)k \left(\frac{\partial \theta}{\partial r} + \frac{\partial^2 \theta}{\partial r^2} dr \right)$$

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The difference of these two quantities should be equal to the heat quantity which was employed to raise the temperature of the thin cylinder, and we have

$$\frac{\partial \theta}{\partial t} = \frac{k}{c_0 \rho_0} \left(\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r} \frac{\partial \theta}{\partial r} \right) \dots \dots \dots (7).$$

Vieille and Liouville¹⁾ have solved this equation under the assumption of $r=\infty$ to find out the temperature of gun wall at any given point at time t , thus

$$\theta = Ce^{\frac{c_0 \rho_0 m^2}{k} t - m r} \dots \dots \dots (8),$$

where C and m are constants depending on the physical properties of the material and initial temperature of the gun wall.

From these equations we can conceive the heating phenomena in gun wall, where the physical properties of material play an important part. The temperature of thin cylinder imagined on the surface of bore increases with the surface conductivity and the temperature of explosion; it is inversely proportional to the density and the specific heat of material, as we can see from eqn. (6), which is obtained under the assumption that during the time δt there is no flow of heat through the outside of the thin cylinder, so that the temperature of thin cylinder should be lower actually

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1) Vieille:—l. c. p. 208.

than is expressed by (6). Besides this, the heating of the thin cylinder depends much upon the velocity of hot gas blowing over the surface of bore; because the gas particles lose a certain amount of their heat by heat conductivity of gun wall; hence the higher the velocity of the flowing gas the more quickly are the cooled particles replaced by hot, the temperature of the gun wall being raised inconsequence. Thus the leakage of gas having enormous velocity of flow through a narrow path, such as erosion cracks or the space between driving band and gun wall, is liable to melt off a thin layer of material. From equation (7) showing the velocity of heating of gun wall we learn also that when the thermal conductivity of the material is very large the gun wall cools more rapidly. Besides the heating by hot gas there is another heating due to the friction between the driving band of projectile and the surface of bore.

VI. Thermal stress in gun wall.

As we have seen from equation (8) the temperature of gun wall varies as a function of time and radius, so that at any given instant, where no steady flow of heat is expected, we can, whether the projectile remains still in the bore or not, find the distribution of temperature in gun wall as a function of radius only. The stress caused by this temperature distribution at a given instant is easily calculated in the case of a hollow cylinder. For a hollow cylinder having internal and external radii of r_1 and r_2 respectively, heated in such a manner that the temperature varies with the radius only and not in the direction of the longitudinal axis, we have the following¹⁾:—

1) M. Ôkôchi:—Ueber die Wärmespannung im Geschützrohre. Proc. Tokyo Math.-Phys. Socie. 2nd. Ser., Vol. VIII, No. 18, p. 534.

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$$\left. \begin{aligned} \sigma'_r &= \frac{m E a}{m-1} \frac{r_1^2 r_2^2}{r_1^2 - r_2^2} \left[\frac{1}{r_1^2 r_2^2} \int_{r_2}^{r_1} \theta r dr - \frac{1}{r_1^2 r^2} \int_r^{r_1} \theta r dr \right. \\ &\quad \left. - \frac{1}{r_2^2 r^2} \int_{r_2}^r \theta r dr \right] \\ \sigma'_\varphi &= \frac{m E a}{m-1} \left[\frac{r_1^2 r_2^2}{r_1^2 - r_2^2} \left(\frac{1}{r_1^2 r_2^2} \int_{r_2}^{r_1} \theta r dr + \frac{1}{r_1^2 r^2} \int_r^{r_1} \theta r dr \right. \right. \\ &\quad \left. \left. + \frac{1}{r_2^2 r^2} \int_{r_2}^r \theta r dr \right) - \theta \right] \\ \sigma'_z &= \frac{m E a}{m-1} \left[\frac{2}{r_1^2 - r_2^2} \int_{r_2}^{r_1} \theta r dr - \theta \right] \end{aligned} \right\} \dots (9),$$

where σ'_r , σ'_φ and σ'_z are radial, circumferencial and axial stresses respectively; θ is temperature of gun wall expressed as a function of radius only; a , E and $\frac{1}{m}$ are coefficient of thermal expansion, modulus and Poisson's constant of the material respectively; for the sake of simplicity these are assumed to be constant and independent of temperature.

We have considered the thermal stress only in the gun wall, but in built up and wire guns there exists another stress due to the internal gaseous pressure when under fire and the shrinkage stress and stress produced by the wire winding when at rest. If r_1 and r_2 be the internal and external radii of the inner tube respectively, we have for the total stresses under fire in radial, circumferencial and axial directions

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$$\left. \begin{aligned} \sigma''_r &= \frac{(P_1 - P_2) r_1^2 r_2^2}{r^2 (r_2^2 - r_1^2)} - \frac{P_1 r_1^2 - P_2 r_2^2}{r_2^2 - r_1^2} - \sigma'_r \\ \sigma''_\varphi &= \frac{(P_1 - P_2) r_1^2 r_2^2}{r^2 (r_2^2 - r_1^2)} + \frac{P_1 r_1^2 - P_2 r_2^2}{r_2^2 - r_1^2} + \sigma'_\varphi \\ \sigma''_z &= \frac{r_1^2 P_1}{r_2^2 - r_1^2} + \sigma'_z \end{aligned} \right\} \dots \dots \dots (10),$$

in which P_1 and P_2 are internal and external pressure for the inner tube, the axial stress being considered as uniformly distributed over the cross section of inner tube. At the surface of bore, making $r=r_1$, the equations (10) become

$$\left. \begin{aligned} \sigma''_r &= P_1 \\ \sigma''_\varphi &= \frac{P_1(r_1^2 + r_2^2) - 2P_2r_2^2}{r_2^2 - r_1^2} + \frac{mE\alpha}{m-1} \left[\frac{2}{r_1^2 - r_2^2} \int_{r_2}^{r_1} \theta r dr - \theta_0 \right] \\ \sigma''_z &= \frac{r_1^2 P_1}{r_2^2 - r_1^2} + \frac{mE\alpha}{m-1} \left[\frac{2}{r_1^2 - r_2^2} \int_{r_2}^{r_1} \theta r dr - \theta_0 \right] \end{aligned} \right\} \dots (11),$$

from which we see that when the temperature of internal surface of gun wall is higher than that of the external, the second term is always negative and compressive stress exists in both circumferential and axial directions. Accordingly the stresses in these directions on the surface of bore under fire are reduced by the temperature stress. When the internal pressure becomes very low, while the blowing of hot gas in bore and the heating of gun wall continues though the projectile has already left the muzzle off, the second term becomes greater than the first; and when the internal pressure disappears the equations (11) become

$$\left. \begin{aligned} \sigma''_r &= 0 \\ \sigma''_\varphi &= -\frac{2r_2^2}{r_2^2 - r_1^2} p_2 + \frac{mE\alpha}{m-1} \left[\frac{2}{r_1^2 - r_2^2} \int_{r_2}^{r_1} \theta r dr - \theta_0 \right] \\ \sigma''_z &= \frac{mE\alpha}{m-1} \left[\frac{2}{r_1^2 - r_2^2} \int_{r_2}^{r_1} \theta r dr - \theta_0 \right] \end{aligned} \right\} \dots (12),$$

in which p_2 is the external pressure due to the shrinkage or wire winding at rest acting on the external surface of inner tube.

We learn from the equations that when the temperature of inner surface of gun barrel is higher than that of the external, the second term being always negative, there will be a very large

compressive stress exerting on the internal surface. After repeated firing the gun barrel is heated to a very high temperature, it may then be suddenly cooled by cold water ejection into its bore, or by circulating water in a hose surrounding the gun barrel externally. In the former case the compressive stress at present under discussion disappears suddenly on the internal surface of bore and a tensile stress is produced. On the contrary, in the latter case, the compressive stress existing on the surface of bore is much increased by the external cooling.

VII. Thermal expansion and transformation of steel.

We have seen in the above equations that the temperature stress increases with the thermal expansion coefficient, which is generally considered almost constant up to the temperature of A_1 transformation for steel; but an abnormal change of dilatation is observed at this temperature of transformation. The author¹⁾ has conducted some experiments, collaborated with Messrs M. Majima and N. Sato, in connection with the thermal dilatation of several kinds of gun steel at high temperatures, in which the specimen was found to expand up to transformation point and then suddenly begin to contract until the structure became completely austenic; after that again it expanded as temperature increased. Thus the specimen, when cooled at γ state, contracts until the temperature of A_{r_3} transformation, and then expands suddenly in changing to α state.

The thermal stress caused by these abnormal dilatations can be no longer expressed by the equations (9). The stresses in such

1) M. Ôkôchi, M. Majima and N. Sato:—Molybdenum steel versus gun erosion. Jour. of the College of Eng. Tokyo Imp. Univ. Vol. IX, No. 5, p. 160.

case depend also much upon the coefficients of contraction and of expansion at A_c and A_r transformation respectively. In carbon steel the aspect of abnormal dilatation at the transformation temperatures is modified by the carbon content. The results obtained by Prof. Honda¹⁾ are reproduced in Fig. 3; the ordinate represents the elongation per unit length and the abscissa the temperature. To avoid the overlapping of the curves, they are drawn one above another and only represent portions near transformation temperatures.

As we see from figure 3 the contraction and expansion at transformation temperatures are not represented by smooth curves, but we can calculate approximately the coefficients of the expansion and contraction by drawing a tangent at the point almost corresponding to A_{c_2} and A_{r_2} transformations. The results are tabulated in the Table II together with the total amount of expansion and contraction measured from the diagram.

Fig. 3.

1) Kôtarô Honda:—On the thermal expansion of different kinds of steel at high temperatures. Sci. Reports Tôhoku Imp. Univ. Vol. VI, No. 4, p. 203.

TABLE II.

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Material	Coef. of cont.	Coef. of expan.	Total cont. in mm.	Total expan. in mm.
Swed. iron	1.10×10^{-5}	2.50×10^{-5}	5.63×10^{-3}	7.25×10^{-3}
0.14% C	1.06 „	2.13 „	5.63 „	7.63 „
0.18	1.06 „	1.92 „	6.25 „	9.63 „
0.31	2.94 „	1.78 „	15.60 „	15.75 „
0.44	3.75 „	2.43 „	13.10 „	14.63 „
0.56	4.44 „	3.88 „	14.40 „	16.50 „
0.64	4.88 „	5.50 „	12.50 „	12.25 „
0.75	∞	∞	12.50 „	15.13 „
0.80	∞	7.08 „	11.60 „	12.13 „
0.94	16.30 „	4.33 „	9.38 „	11.13 „
1.02	8.13 „	8.75 „	13.00 „	13.13 „
1.30	9.06 „	7.50 „	9.38 „	11.26 „
1.50	8.44 „	∞	10.60 „	15.50 „

From these results we observe that the coefficient of contraction increases with carbon content in low and medium carbon steels. For various kinds of steels for gun material the following table is computed ¹⁾.

TABLE III.

九八(横)

Material	Coef. of cont.	Coef. of expan.	Total cont. in mm.	Total expan. in mm.
Mo. steel Mo. 1.6% C 0.61%	6.93×10^{-5}	5.90×10^{-5}	8.20×10^{-3}	11.8×10^{-3}
Ni-Mo. st. Ni 1.02% Mo. 3.65% C 0.54%	11.0 „	6.72 „	18.7 „	22.8 „

1) M. Ôkôchi, M. Majima and N. Sato :—I. c.

Material	Coef. of cont.	Coef. of expan.	Total cont. in mm.	Total expan. in mm.
Ni steel Ni 3.55% C 0.59%	12.0×10^{-5}	7.2×10^{-5}	14.3×10^{-3}	10.5×10^{-3}
W steel W 2.38% C 0.62%	6.67 „	7.2 „	10.4 „	10.8 „

The coefficients of contraction of molybdenum and tungsten steels are remarkably small compared with those of nickel and nickel-molybdenum steels. The mode of abnormal dilatation will

Fig. 4.

be influenced by the heat treatment of the material before the experiment, as we observe usually in grey cast iron, in which the amount of contraction at A_c transformation decreases gradually with repeated heating and cooling and finally disappears¹⁾. It is not clear whether the rate of heating or cooling may affect the mode of dilatation at transformation temperatures or not. To solve this question an experiment was carried out where the specimens were heated more quickly than in the previous experiments, but no change of the coefficient of contraction and expansion was observed. The results are shown in figure 4, in which the duration of heating or cooling is noted.

1) A: paper on the thermal dilatation of grey cast irons will be published a little later by the author.

In actual firing a thin layer of the material on the surface of gun bore is heated very quickly by the hot gas produced by the combustion of powder charge as well as the friction of driving band. If the temperature of this thin layer reaches the transformation temperature contraction of the layer will take place in all directions, causing enormous tensile stress on account of the adjacent parts of the gun wall remaining still at a temperature close to but just below the transformation. Accordingly it follows that the remaining part of the gun wall is subjected to a compressive stress. Again when the gun is cooled after firing, the thin layer is subjected to compressive stress due to its own expansion at the temperature of transformation, while the remaining part of the gun wall is subjected to tensile stress.

Now we shall calculate the stress derived from the transformation of structure of the material on the internal surface of gun barrel. On the surface of bore imagine a thin cylinder having thickness dr , the land and groove of the rifling being disregarded, and assume that, by the direct heating of the hot gas, the thin cylinder is uniformly heated just to the temperature of transformation while the remaining part of the gun wall is still left at

Fig. 5.

a lower temperature so that the contraction of the above imagined thin cylinder is interrupted by the boundary surface. Figure 5 shows a virtual cylindrical element taken from the thin cylinder, gun axis being Z axis; the inner surface coincides with that of the bore having an area $rd\phi dz$, while its outer surface is expressed by $(r+dr) d\phi dz$. The normal stress

and the shearing stress on the inner surface of the element due to the contraction are evidently nil, so that if the thickness dr is sufficiently small, the stresses on the surface of $(r+dr)$, $d\varphi dz$ can be neglected in comparison with the circumferencial and axial stresses acting on the surfaces of $drdz$ and $\left(r+\frac{dr}{2}\right)d\varphi dr$ respectively. Let σ_φ and σ_z circumferencial and axial stress, then we have from the genelar equation for stress and strain,

$$\begin{aligned}\sigma_r &= \frac{Em}{m+1} \left(\varepsilon_r + \frac{e}{m-2} \right) = 0 \\ \sigma_\varphi &= \frac{Em}{m+1} \left(\varepsilon_\varphi + \frac{e}{m-2} \right) \\ \sigma_z &= \frac{Em}{m+1} \left(\varepsilon_z + \frac{e}{m-2} \right),\end{aligned}$$

where ε_r , ε_φ and ε_z are radial, circumferencial and axial strain respectively, e volume dilatation, E modulus of elasticity and m Poisson's reciprocal. From the first equation we have

$$\varepsilon_r + \frac{\varepsilon_r + \varepsilon_\varphi + \varepsilon_z}{m-2} = 0 \quad \text{or} \quad \varepsilon_r = \frac{\varepsilon_\varphi + \varepsilon_z}{1-m}$$

and introducing this value of ε_r in place of the second and third equations we have

$$\begin{aligned}\sigma_\varphi &= \frac{Em}{m^2-1} (m\varepsilon_\varphi + \varepsilon_z) \\ \sigma_z &= \frac{Em}{m^2-1} (\varepsilon_\varphi + m\varepsilon_z).\end{aligned}$$

If the contraction of the thin cylinder is completely prevented by the boundary surface then, α being the coefficient of contraction and ΔT the temperature gradient, we have

$$\varepsilon_\varphi = \varepsilon_z = \alpha \Delta T,$$

so that

$$\sigma_\varphi = \sigma_z = \frac{Em}{m-1} \alpha \Delta T \dots\dots\dots (13).$$

From which we see that the tensile stresses in both directions are

equal to each other. Hence when the thin cylinder breaks down under these tensile stresses, most cracks on the land of rifling should be perpendicular to the gun axis because the contraction on the surface of land is impeded in the axial direction only and is free in the circumfrenclal direction. On the contrary, the contraction of bottom of grooves is comparatively unrestrained in the axial direction but interrupted in the circumferencial direction by the lands of rifling, so that the longitudinal cracks result at the bottom of the grooves,

The compressive stress in the thin layer on the surface of bore due to its own expansion in the case of cooling of gun barrel may be calculated in the same manner and is expressed also by equation (13), but the directions of the stresses are reversed and α represents the coefficient of expansion. The tensile and compressive stresses due to transformation appear alternately at each round as the gun barrel is heated and cooled.

These stresses caused by the transformation of the material and expressed by equation (13) are proportional to the coefficient of contraction or expansion when the temperature gradient and the elastic constants are the same. In ordinary gun steel, therefore, the stress increases with carbon content, and in nickel or nickel-molybdenum steels the stress is much greater than that of ordinary gun steel¹⁾, (See tables II and III).

VIII. On the causes of crack formation.

It is evident that the cracks on the surface of bore are formed mechanically, not chemically, and we may point out the following items as the causes of their formation :

1) M. Ôkêchi, M. Majima and N. Sato :—l. c. p. 169.

1) The temperature stress due to the unequal heating of gun wall is expressed by the equations (9) and (12). The rupture of material may be produced by the compressive stress when the temperature of the inner surface of gun barrel is higher than that of the external. After repeated firings the gun piece is heated and when the bore is suddenly cooled by cold water injection, then the effect of tensile stress is to cause the cracks on the surface of bore.

2) Owing to the direct heat action of hot gas and the friction of driving band, the thin layer on the inner surface of bore will be heated beyond the temperature of A_{c_1} transformation, while the other part of the gun wall remains still at a lower temperature. The tensile stress due to sudden contraction at transformation temperature as expressed by the equation (13) is sufficient to produce the cracks, because the coefficient of contraction is very large in this case. The transverse cracks must be expected on the land and the longitudinal cracks at the bottom of the grooves of rifling. The circumferencial stress under fire is increased by the gaseous pressure, thus

$$\frac{P_1(r_1^2 + r_2^2) - 2P_2r_2^2}{r_2^2 - r_1^2} + \frac{Em}{m-1} \alpha \Delta T,$$

which must be far greater at the roots of both the driving and loading sides of rifling, for the intensity of stress distribution in such a figure as the cross section of rifling part is most severe at the roots of the land, while the above equation is calculated for smooth bore.

3) The deep and wide longitudinal cracks sometimes found at the root of the driving side are fairly well explained as the result of the above reasoning combined with the consideration of

the large stress due to the rotational acceleration of the projectile, which affords a normal force expressed by the equation (4) on the driving side of the rifling.

4) When thin martensitic structure is formed on the inner surface of bore, the formation of cracks due to the causes stated above must be much facilitated on account of the brittleness of the martensitic structure. It must also be noted that the martensitic structure is in an expanded state compared with the original α state¹⁾, so that the martensitic structure exerts compressive stresses in both axial and circumferencial directions owing to its own expansion. These compressive stresses are always accompanied by the other compressive stress due to the shrinkage or wire winding as expressed by the equation (1) and disappeared under fire by the gaseous pressure.

IX. Conclusion.

Summarising the above results, the causes of gun erosion, which means the enlargement of diameter of bore and deformation of the surface of bore, can be enumerated as follows:

1) The chemical action of combustion gas, though the time of its action is instanteneous, may be considered as a cause of gun erosion, the pressure and temperature being very high. It is however not a serious factor.

2) The partial melting of gun barrel owing to the leakage of high temperature gas through the narrow path between the driving band and surface of bore.

3) The cracks on the surface of bore play the most important rôle in gun erosion. We have seen in VIII that the cause

1) M. Ôkôchi, M. Majima and N. Sato :—l. c.

of their formation is mostly the stress resulting from the transformation of structure of steel. Further reason has been shown why the higher carbon steel is more erosive than low carbon steel, and why nickel or nickel-molybdenum¹⁾ steel has less resisting power against gun erosion than ordinary gun steel. A comparatively longer life of bronze gun can also be explained by the fact that there is no crack produced by the transformation of material.

4) The wear of material on the surface of bore owing to the enormous friction produced by the motion of projectile.

The writer wishes to express his thanks to Mr. N. Sato for having carried out the observations of thermal dilatation of various materials. He would also like to mention here that all the expenses connected with this investigation have been defrayed by a grant from the Department of Education for the encouragement of Scientific Research.

Ordnance Engineering Laboratory,
Tokyo Imperial University.
Nov. 1918.

1) Some experiments were carried out in Japan with regard to the resisting power of nickel- and nickel- molybdenum steels against gun erosion; the details of these experiments are, however, not yet published.

講

討 論

演

大砲のエロージョン

○會長(寺野精一君) 唯今「ガンエロージョン」の問題に付て大河内博士の面白い御講演がありました、御質問なり御意見がございましたれば御述べを願ひたいと思ひます。

○田路坦君 唯今大河内博士から「ガンエロージョン」のことに付きまして大變有益な御講演がございました、私は専門でございませぬから精しいことは能く存じませぬが「インテレスト」を有ちまして考へます所に依りますと一番初め仰つしやいました露西亞の實驗でございしますが「セオリーオブオルタネートストレス」に依る「ガンエロージョン」是は唯今「サーマルストレス」のことや又「コンプレッション」、「イニシアルコンプレッション」即初め「ガン」を造ります時出来た「コンプレッション」其他種々の「ホース」が働いて、それが「オルタネチーブ」に働いて來るのであると云ふ説ではないかと思ひますが、此説は御承知の如く「オルタネートストレス」の場合は唯今御伺ひ致しました所では可なり大きなものが働いて居るのでございますが、併しそれは矢張り「レヤーケース」でありまして「ゼネラルケース」としては「レンジ」を少し越えた所に來て居りはしないかと思考いたします、さうすると「オルタネートストレス」の場合に於きましては「ガン」の内部に「クラック」が出来て來るやうにはちよつと考へられぬやうに思ひます。此邊の精しいことは私は不幸にして存じて居りませぬ。それを承知いたしたいと思つて居ります。其次に「リューブリカント」に「グラフィット」を附けるとか若くは「オイル」を附けるとか云ふ問題でございします。是は「ライフル」の中に「グラフィット」を入れて置くことであらうと思ひます。若しさうでないとしたらあとから矢張り火藥の瓦斯や其他を吹き出します。果して「メカニカル、リュブリケーション」が有效であるならば「オイル」ばかりでなく其外何か「レライアブル」の方法が無ければならぬものであらうと思ひます。それから「フリ

クシヨシ」のことに付て少々分りませぬことがございます。要するに「フリクシヨシ」に關しますことは能く分つて居ないのではなからうかと思ひますさうして「ノーマルフリクシヨシ」に關しますことは是は「ライフル」を切つてあるものと切つてないものと比較いたしまして、二つの「シリンダー」から實驗いたしますれば或程度まで分るものではなからうかと信じて居ります。それから「タンゼンシャル」と申しますか——横の方から入つて来る「ノーマルフリクシヨシ」是は「ローテシヨシ」から參りますものでありますから可なり面倒と存じます。此「フリクシヨシ」に關することは私の考では今少し實驗及「セオリー」を入れましたならば結果が得られはしないかと考へて居ります。それから「ヒート」の「コンダクチーブ」に對しましては相當の「サッポジシヨシ」の下に「カルキューレート」されたもので有りますが先程御書き下さいました「フォーミュラー」から $\frac{\partial \theta}{\partial r}$ を取つて見ますと是は「レジアル」に變つて行く「テンペレーチャー」の變り方で是が「フォーミュラー」に實際現はれました所に依りますと餘り急激に變つて來ないやうであります。是は只「エキスポネンシアル」に變つて來る、尙ほ「 r 」は大きな「バーア」になつて居ないやうであります。さうしますと唯今御書き下さいました「テンペレーチャー」の「フォーミュラー」は實際「マルテンサイド」が起ると云ふ「サッデンクーリング」と申しますか兎に角非常に速い變化で實際出來たものは此「テンペレーチャー」の「カルキューレシヨシ」から出して御いでになつた「フォーム」と少し一致して居らなからうかと存じます。然し「マルテンサイト」の出來ますことは私だけの考では可なり有力なる「セオリー」ではなからうかと存じます。初めの「ビューユ」の「テーブル」に致しましても、唯今御話のやうに「コンダクチーブ」若くは「エロンゲーシヨシ」の問題でなく、どんなものから「マルテンサイド」が出來て來るか云ふと「ニツケル、クローム」など澤山ある所に一番餘計來るやうでございます。それだから「ビューユ」の實驗は「マルテンサイド」の説明をして居りはしないかと考へます。それから「テーブル」三で以て唯今「サーマルコンダクチビチー」で出來ました「コントラクシヨシ」若くは「エロンゲーシヨシ」に

關しまするものも能く「ケミカルコンポーネント」を研究して見ませぬと分りませぬが矢張り大分「マルテンサイド」が餘計出來て来るやうに思ひます。それから「サーマルトランスフォーメーション」に關しまする問題は甚だ潜越てございますが、少し疑はしい所がありはせぬかと云ふ考てでございます。是は別問題でございますが「エイワントランスフォーメーション」是は「タイム」が速くなりました場合は「トランスフォーメーション」が一致して來まることが或場合大分出て來ます。従て火藥の「コンパッション」が速いときは唯今大河内博士の仰つしやいました非常な短時間の中に實驗しなくてはならぬことでありますから非常に困難なことて、其邊は御察し致して居りますが、其點は實は能く分つて居りませぬ、相當の「タイム」で考へられましたら今の「サーマルトランスフォーメーション」に關しまする問題は多少私の考ては疑を挾むと申しては何てでございますが、少し不十分な風に考へられはしないかと思つて居ります。其邊は自分も此問題を専門に研究して見たのでござませぬから分りませぬてございますが、御教示を得られましたら大變幸てでございます。

○大河内正敏君 「チェルノッフ」の「セオリー」は「オルタネートストレス」でありませぬ、「ヒート」の爲に「エキスパンド」する、熱の爲に「エキスパント」すると云ふ事が土臺です、それから今度「クール」した爲に「コントラト」する。斯う云ふ工合に詰り「オルタネートストレス」と云ふよりは「ヒートストレス」のやうな説でありますが、私は此説に矛盾がある、なぜならば「エキスパンション」して「テンション」が出來ると云ふやうに取れる、併し「サーフェースコンプレッション」が起らなければならぬ、それが「テンション」が起つて自分で割れると云ふ意味に取られるやうに書いてあります。私のその所の言ひ方が混同したかと思ひます。それから「グラファイト」の問題であります。亞米利加で「グラファイト」を大砲の中に入れて撃つが宜いと云つて居る、無論入れて撃つのも一つの方法であります。御話の如き方法に依つて塗ることは「エフィシェンシー」が宜いのであります。併し一方に於て亞米利加で「グラファイト」は役に立たぬ、それより「オイル」が宜いと

云ふことを言つて居ります、實際此問題ははつきり極つて居りませぬ。亞米利加で此問題の研究をやりました「レポート」は昨年頃からボツボツ専門雜誌に出て來たのであります。何分實驗をやりますに金が掛りますし時間も掛りまして容易に片が付かぬ問題であります。それから「フリクション」の問題であります。御承知の通り「フリクション」は「ローテーション」によるのは今のやうに勘定すれば出來ますけれども「ラジアルストレス」の爲めの「フリクション」は是はむづかしい、「マテリアル」が彈丸の運動中に減して仕舞ひますから餘ほど勘定がむづかしいと思ひます。謂はゆる「セオリーオブプラスチック」の問題になりますからちよつと勘定がしにくいと思つて居ります。それから「ヒートコンダクチャーピッチ」の問題、是は御話の如く「ヒーティングベロシティー」と云ふものが出て來ます。是は「ビエュ」の勘定でございます、「ヒーティングベロシティー」は餘り大きなものではないと思ひます。御話の如く私は「マルテンサイト」が自分で以て急に冷却の爲めに出來ると云ふことはおかしいと思ひます、併し一方「マルテンサイト」が出來て居るから急に冷却されるものと考へなければなりませぬ。結局問題は「ソフトスチール」で作つた大砲と「ハードスチール」の大砲と同じやうに撃ちまして、さうして「マルテンサイト」にどう變るかと云ふ比較試験をやらなければならぬと思ひます。それを一向やつて居りませぬ。それから「トランスフォーメーション」の問題であります。是は實驗「ラビッドヒート」が出來ませぬから何とも謂へませぬ。

○會長(寺野精一君) 御質問を伺つて居りますと、あとの問題と大分關聯して居りますから續いてあとの御講演を願ひます。

○會長(寺野精一君) 唯今の大河内博士の御講演に對して御質問がございませうれば時間が切迫いたして居りますから成るべく簡単に御述を願ひたいと思ひます、……御質問或は御討論はございませぬか、……別段御質問御討論も無いやうでございませうから、ちよつと一言大河内博士に御挨拶申し上げます、本日大河内博士は非常に有益な御講演をなさつて下されまして殊に「カンエロージョン」と云ふ斬新なる問題の御研究を御發表になり又次では「カ

討 ストアイヨン」の「グロース」と云ふ甚だ珍しい問題で御講演下されまして
本會員の爲に有益なる參考資料を得ましたことを深く感謝します。茲に諸君
と共に拍手して御禮を申し上げたいと存じます。〔一同拍手〕

論

大砲のエロージョン

Plate I.

G L G L G L G L G L G

Photograph of a gutta-percha impression taken from eroded gun barrel
at the origin of rifling. G is groove and L is land.