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PHYSICOCHEMICAL ASPECTS OF GUN BARREL EROSION AND ITS CONTROL

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BENET WEAPONS LABORATORY
WATERVLIET ARSENAL
WATERVLIET, N.Y. 12189

TECHNICAL REPORT

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Gun tube erosion can be defined as the bore surface damage and bore enlargement caused by firing, which can lead to loss in accuracy and the effectiveness of the weapon. It is one of the two major factors on the basis of which gun tubes are condemned; the other factor being fatigue life. Erosion is a complex phenomenon resulting from the interaction of propellant gases and the projectile with the surface of the bore. The bore surface is exposed for a short time to temperatures approaching the melting point of

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20. steel, pressures as high as 50,000 psi, reactive atmosphere composed of CO, CO_2, H_2O, H_2, N_2, and numerous other identified and unidentified constituents. Superimposed on these conditions are the high velocity of gases and swaging action of the projectile rotating band. It is the objective of this presentation to review the physicochemical processes involved in erosion and indicate some critical areas which need further investigation. Also, various efforts to control erosion in barrels will be briefly discussed.

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Gun tube erosion can be defined as the bore surface damage and bore enlargement caused by firing, which can lead to loss in accuracy and the effectiveness of the weapon. It is one of the two major factors on the basis of which gun tubes are condemned; the other factor being fatigue life. Erosion is a complex phenomenon resulting from the interaction of propellant gases and the projectile with the surface of the bore. The bore surface is exposed for a short time to temperatures approaching the melting point of steel, pressures as high as 50,000 psi, reactive atmosphere composed of CO, CO_2, H_2O, H_2, N_2, and numerous other identified and unidentified constituents. Superimposed on these conditions are the high velocity of gases and swaging action of the projectile rotating band. It is the objective of this presentation to review the physicochemical processes involved in erosion and indicate some critical areas which need further investigation. Also, various efforts to control erosion in barrels will be briefly discussed.

Introduction

There are two basic factors which limit the safe and effective life of a gun tube.

1. Fatigue: The mechanical properties of the tube material deteriorate as a result of thermal and stress cycling set by firing. After a certain number of rounds, a crack initiates and then propagates at a slow rate followed by an accelerated rate until the tube, depending upon the properties of the material, fails either by perforation or catastrophically.
2. Erosion: Defined as the progressive damage or enlargement of the bore surface (Figure 1) as a result of firing, erosion, after a certain point, will result in loss of accuracy and muzzle velocity and, therefore, effectiveness of the weapon.

The purpose of this paper is to review salient physicochemical processes involved in erosion and its control and bring some challenging problems to the attention of investigators in the field of high temperature, gas-metal reactions in mixed environments. Because of limitation of space and scope of the symposium, only a bird's-eye view of the subject will be given. For more details, the readers can profitably consult References 7 and 8.

Historical Background

Ever since the invention of the gun, erosion has been recognized as a serious problem. Consequently, continuous improvement of the material of the construction of the barrel and propellants has been sought. For example, barrels are now made from specially thermomechanically treated steels instead of bronze or cast iron and the smokeless powders of various descriptions have replaced the old gun powder. Systematic studies on erosion date as far back as the end of the 19th century. These have been covered in excellent reviews such as in References 1 through 6. The most exhaustive and authentic work was done during World War II (1941-45) under the sponsorship of Division 1 of the National Defence Research Committee of the Office of Scientific Research and Development, Washington, D. C. The results were reported in a Summary Technical Report (7) entitled, "Hypervelocity Guns and Control of Gun Erosion." Although considerable insight was gained into the processes involved in erosion and some measures to control it were developed, it remained, nevertheless, an incompletely understood phenomenon and no satisfactory measures to control it were established. Progress made during 1946-70 was reviewed at the Interservice Meeting on Gun Tube Erosion and Control held at the Watervliet Arsenal in February 1970 (8). The essential conclusions of this review were that, since 1946 no real advancement was made in further understanding the erosion phenomenon and, until then, no propellant-bore surface material system was available which could stand the currently used firing schedules without considerable erosion damage.

Magnitude of the Erosion Problem in Conus Weapons

The magnitude of the cost of erosion to the defense efforts of this country can be appreciated from the fact that many large caliber guns and most of the rapid fire machine guns are condemned because of erosion much prior to reaching their fatigue life. The majority of the exploratory and advanced weapons are known to be seriously handicapped by erosion. It is expected that the problem of erosion will remain and even increase in complexity in the future because of the ever-increasing demand of higher muzzle velocity, higher rates of fire, and long bursts in the advanced weapons.

What is Involved in Erosion

Figure 2 illustrates the three major elements involved in the process of erosion, namely: (1) Gun steel at the bore. (2) Propellant (also the primer and the igniting powder) which could be a single base or a double base. (3) Projectile with its rotating band (usually copper-zinc alloy). The representative composition and properties of the presently used gun steel and composition of representative propellants are also shown.

When the gun is fired, the propellant burns and develops a high temperature (2500-3700°K), and a high pressure (20-60,000 psi) due to the formation of a large volume of gases which propel the projectile and give it the required muzzle velocity. Figure 3, as an example, shows the variation (9) of temperature, pressure, muzzle velocity, and the fraction of the propellant burnt in a 3-inch gun as a function of time prior to the ejection of the projectile which is indicated as zero time.

CO, CO_2, H_2O, H_2, and N_2 are the major constituents of the powder gas. Also present are small amounts of NH_3, CH_4, NO, and H_2S (from the primer), and perhaps a number of unidentified free radicals, ions, and metastable molecular species. The amount of CO, CO_2, H_2O, and H_2 is controlled essentially by a water-gas reaction

$$CO_2 + H_2 \rightleftarrows CO + H_2O \qquad (1)$$

Under firing conditions it can be expected that the reactions in the gas phase are not fast enough to establish equilibrium composition of the gas at the temperature of the bore surface immediately. Therefore, the composition of the gas reacting with the bore surface corresponds to somewhat higher temperature than that of the bore surface. The CO/CO_2 ratio, in general, for the single base powders is higher (2-3) than that for the double base (approximately 1). In other words, the single base powders are less oxidizing than the double base powders.

Figure 4 summarizes the various interacting parameters to which the bore surface is subjected to. These include:

1. Temperatures as high as 2500-3500°K.
2. Pressures 20-50,000 psi.
3. Severe chemical reactions of powder gas.
4. Severe mechanical stresses because of 2 and swaging action by the accelerating projectile.
5. Sweeping action of gases on the softened or chemically interacted bore surface.
6. Improper obturation resulting in high velocity and high temperature gases streaming past the projectile.
7. Abrasive action of the unburnt powder or loosened gas-metal reaction products.
8. Combined action of any or all of the above conditions.

It has been estimated that in an average gun tube the temperature at the bore surface may rise at the rate of 10^6 °C/sec, and the rate of pressure rise could be as high as 10^5psi/sec. Therefore, most of the processes occurring at the interface of the gas and metal do not occur under equilibrium conditions.

Further complexity is added by the fact that these conditions vary along the length of the tube. The severest conditions occur near the origin of the rifling (O.R.) and, therefore, this is the most affected area in the tube. Erosion at the muzzle could critically influence the exterior ballistics, but the muzzle erosion is generally very little as compared with O.R. erosion.

It may be of interest to point out that the product of the time of the ballistic cycle and the maximum life of a gun tube in terms of a number of rounds, is approximately 10-20 seconds for the majority of guns. In other words, the steel at the bore surface stands the firing environment for only 10-20 seconds during the life of a gun barrel. This is indicative of the severity of environment and the poor behavior of gun steel, the only material used to fabricate guns.

Some of the important processes which result from the above listed parameters in the area of the origin of rifling (Figure 4) are very briefly discussed below.

Thermally Altered Layer

Heat and pressure cycling result in the transformation of martensite (>750°C) $\rightleftarrows$ austenite, which, on cooling, depending upon the rate of cooling, revert back to martensite. The thickness of this layer, which is also called the thermally altered layer and has the same composition as that of the unaltered layer, varies along the bore of the tube.

Heat Checking

Consequent to the volume changes on rapid heating and cooling of the surface, also involving phase transformation, stresses are developed at the bore surface which are relieved by the cracking of the surface. This condition is called heat checking (Figure 4b). It is further aggravated by the combined chemical interaction and high temperature (higher than the m.p. of the product formed at the surface) causing pebbling (Figure 4c), especially in the forward part of the chamber.

White Layer

The powder gases react with the thermally altered layer and form a thin layer of the product called "white layer" (Figure 4d). Its composition varies with the history of firing, nature of the propellant, and the tube temperature. With a single base propellant, the major products formed are Fe_3C (cementite), Fe_2N_χ (epsilon), and Fe_4N (γ prime), some austenite stabilized by the dissolved C and N, and martensite phase formed on rapid cooling of austenite. Fe_2N_χ and Fe_4N are unstable at the temperatures of firing. Therefore, these possibly form during the cooling time by the interaction of NH_3 with the bore surface.

Another layer between the thermally altered and white layer (called the inner white layer) is also observed. It is generally austenite stabilized by the dissolution of C and N, and is sometimes partly melted. Apparently, the formation of the inner layer precedes the formation of the outer one. The morphology of the layer is schematically represented in Figure 4a.

With double base powders, the predominant end products are austenite and FeO which, however, because of the high temperature may melt along with the bore surface and be removed by the gases.

Mechanical Action of the Gases and the Projectile

The high velocity gases following the projectiles, heat the surface and sweep the softened or molten material from the bore surface and enlarge its diameter (Figure 4e). Under extreme conditions, actual rippling or formation of "tongues" of molten material is observed. Frequently, incomplete obturation by the rotating band results in very high velocity gases streaming past the projectile which gouge or score the material (Figure 4f). The hot gases will also soften the copper rotating band which, as the projectile moves, results in coppering the bore especially towards the muzzle end. Some of the entrapped copper in the heat check cracks may accelerate their propagation in the body of the material. Further, the accelerating projectile swages the bore, especially the land at the O.R.

Influence of Other Parameters on Erosion

It has been shown that the rate of erosion increases with: 1) increased rate of fire; 2) CO_2/CO and H_2O/H_2 ratios; 3) flame temperature of the propellant; 4) muzzle velocity and increase in chamber-to-bore diameter ratios. The lands are eroded more than the grooves. The origin of the rifling is the worst affected area of the bore. In this region there is more erosion at the 12 o'clock position than at the 6 o'clock. Muzzle erosion is significant only in guns with high muzzle velocity ($>$ 2800 feet per second).

The net results of the combined action of the above conditions are:

1. Enlargement of the bore.
2. Loss of fire accuracy.
3. Loss of muzzle velocity.
4. Also, decrease in fatigue life as the physicochemical environment can accelerate the rate of propagation of cracks formed initially by heat checking.

Suggested Areas of Study in Mechanisms and Control of Erosion

The above is a phenomenological description of typical erosion processes deduced from the post-firing analysis of chemical products of propellant combustion and their interaction products with the bore surface, metallographic examination of the bore surface, and some physical measurements of temperature and pressure at various points in the barrel. For some studies, special erosion gauges were developed to simulate conditions of firing. In other cases actual steel powders mixed with propellant were fired and the recovered products were analyzed chemically and metallurgically.

From such data a number of mechanisms contributing to erosion have been identified and measures of its control have been suggested which, in some cases, proved useful. However, a critical survey of literature reveals that, although considerable work of both theoretical and experimental nature has been done on various aspects of erosion and control during the last century, there are large gaps in the knowledge in certain areas which must be filled before significant progress can be made in achieving the control of erosion. This will be briefly discussed in the following.

Mechanisms

It will be apparent from Figure 4 that gun erosion is a product of thermal, chemical, and mechanical processes. Heat is transferred by convective flow through the turbulent boundary layer of a high velocity mainstream of propellant gases. The characteristic time required for the heat energy to diffuse away from the bore surface is large compared with the ballistic cycle. Therefore, the material in the immediate vicinity of the bore surface undergoes rapid temperature excursions (in some cases the surface temperature may reach as high as 1200°C), resulting in the softening of the bore material. The increase in temperature makes the surface more susceptible to mechanical deformation (under stresses of gas pressure and swaging action of the rotating band on the projectile). Also, it results in the transformation of martensite to austenite (which is more reactive chemically), in diffusion of carbon and nitrogen to form carbides and nitrides which, in general, have a lower melting point than steel, and, also, when propellants with a high flame temperature are used, simple liquefaction of the steel at the surface. In short, the temperature is the regulatory factor for all the erosion processes. It is necessary, therefore, to have knowledge of the temperature profile at the bore surface during the ballistic cycle. Experimental measurements of temperature have been, so far, vitiated by the lack of temperature sensing devices with the requisite fast response time. Semi-empirical relations for heat transfer have been developed by Nordheim, Soodak, Nordheim (10) and others from which a rough estimate of the temperature at the bore surface in certain barrels has been made. However, to arrive at these relationships, equations of heat transfer for a steady state and a fully developed flow have been used despite the fact that the flow in gun tubes is a non-steady state and not fully developed. To simplify mathematics, the boundary layer has been decoupled from diffusional processes in the bore surface by assuming that the wall remained isothermal during the ballistic cycle. The gas flow which is prescribed partly by the interior geometry of the gun tube is not fully characterized for various barrel designs. Therefore, the present state of knowledge about the temperature profiles for specified gun barrel-firing schedules is very empirical and requires both experimental and theoretical studies.

The phenomena of metallurgical transformation on the bore surface, diffusion of carbon and nitrogen, and the formation of carbides, nitrides and oxides described earlier, have been explained essentially on the basis of standard equilibrium thermodynamics. For example, Curtiss and Johnson (11), assuming chemical equilibrium between a finite amount of steel and infinite quantity of reacting gases, have shown that Fe_3C, FeO, and Fe_3O_4 were the ultimate products, the proportion of which depended upon the temperature of the bore surface. Fe_3C predominated at the low temperature while FeO was the main high temperature product. However, the exact mechanism of the reaction at the time of firing and the mass transport from bore surface is not known. In recent years, Richardson, Belton, Rosner, etc. (12) have shown that, due to the formation of the volatile compounds, the rate of vaporization of metals such as Fe, Co, Ni, and W is considerably enhanced in the presence of reactive atmospheres such as $H_2O_{(g)}$ and atomic gases. The contribution of such chemical interactions at the gas-metal interface warrants investigation. Further, it is important that the behavior of materials such as gun steel and other promising alloys against water-gas mixtures, in particular, (with and without the addition of minor constituents such as H_2S and NH_3) at flow rates approaching muzzle velocity be determined. Results from such studies combined with those on heat transfer and gas dynamics can be helpful not only in understanding the mechanisms of erosion, but also in predicting the erosion rates of materials under conditions of gun tube environment.

At the rate of heating and cooling of the bore surface mentioned earlier, equilibrium conditions do not exist in gun tubes. A literature search indicates very little information about the metallurgical phase transformation and chemical interactions under such unsteady state conditions.

The fluctuations of these conditions on the bore surface contribute to the initiation of cracks in the bore which are very critical to the fatigue life of the tube. At the Watervliet Arsenal a capacitor-discharge system (PULSER) has been built to achieve heating rates up to 10^7 °C/sec and cooling rates of 10^5 °C/sec. Using this device, it has been shown that in 4340 steel, the grain boundaries can melt at a much lower temperature (600°C) than the m.p. of steel, thereby loosening the grain which can be easily sheared by the fast flowing gases. The concept is schematically illustrated in Figure 5a. Figure 5b is a micrograph of the surface of an eroded tube clearly showing the melting at the grain boundaries and separation of a grain.

Other contributing factors are rotating band-bore surface interaction, mechanical stresses, and abrasive wear. Their discussion, however, is outside the scope of this review.

Control

In the light of the above mechanisms, two main approaches have been taken to control erosion:

1. Reduction in Bore Surface Temperature: As the bore surface temperature plays the most predominant role in erosion, efforts have been made to reduce it by the following means:

a. Wear Reducing Additives: A sheath of rayon cloth impregnated with wax containing TiO_2 or talc particles is placed at the front end of the cartridge case or the bagged ammunition (Figure 6). On firing, the combustion products of the sheath provide a cooler laminar layer between the powder gas and the bore surface. A polyurethane foam jacket has also proven to be very successful. This technique has worked dramatically in some calibers but not as well in others. Improvement of barrel life as high as 60-100 times has been reported. At this stage no explanation is available because the exact mechanism of the action of the wear reducing additive is not known. Whether TiO_2 or talc act as only dispersants of wax or contribute in some way by absorbing energy or altering the bore surface or the gas composition at the surface is debatable (13).

b. Propellants: Formulation of propellants with low flame temperatures (and also with low erosive constituents) can contribute to minimizing erosion. However, very little effort is being done in this area.

c. Miscellaneous: Other means include external water or air cooling of barrels, applying smear of silicone oils (placed in a capsule in the round), caseless ammunition, liquid propellants, etc., have been used to a limited extent.

2. Erosion Resistant Materials: A very large amount of effort during the last fifty years has been expended to reduce erosion by either improving steel, or using coatings or liner materials with superior erosion resistance. The approach has been essentially empirical. Erosion gauges which, generally, do not simulate gun conditions or actual firing tests, have been used to evaluate the materials. During 1941-45, considerable work was done in this area. The most successful material found was Stellite 21 which was adopted as a liner material for machine guns and is still being used. However, its low melting point has been a limitation when high temperature propellants are used. Mo, especially Mo + 0.1 Co, was indicated as the ideal material, but the technology of fabrication of liners or application of coatings was not developed enough for its successful application. Chromium, which can be easily electroplated, is excellent erosion resistant material, but it is very brittle and as-plated is highly stressed and micro-cracked. On firing, it cracks and flakes off (Figure 7b). Presently, at the Watervliet Arsenal, coatings of cobalt containing 1-4% Al_2O_3

particles applied by electroplating are being evaluated in the M14 rifles. As shown in Figure 7c, which is a view of a barrel surface after 3500 rounds, Co-Al_2O_3 coating does provide protection to the substrate from the erosive environments, acts as a crack arrester and, unlike chromium, it is relatively ductile and does not flake off. Increasing the alpha Al_2O_3 content reduces erosion, but makes the coating susceptible to cracking (Figure 7d). For comparison, the surface of an uncoated tube subjected to the same number of rounds is shown in Figure 7a. However, this work is still in the preliminary stage. Other materials including tungsten, superalloys, and various refractory alloys are being evaluated at a number of R&D centers in the United States. So far, no material which is entirely satisfactory has been reported.

An ideal material which can resist erosion under all conditions of firing will be hard to find because it has to have a high melting point, inertness to thermochemical reactions, mechanical stresses and thermal and mechanical shock, and hot hardness high enough to resist the swaging action of the projectile, yet having some ductility so that it would not crack. Furthermore, the material should be inexpensive and easily fabricable. Considerable advances have been made during the past 25 years in material technology. There is a need for an extensive program to survey and evaluate promising improved or new materials for their behavior in gun barrel environments, especially in high velocity, high temperature water-gas mixtures under steady state and non-steady state conditions. It is highly probable that such a program could lead to some materials which will be superior to the presently used gun steel. There are other minor measures which can minimize erosion, such as selecting rotating band materials which do not interact (chemically or metallurgically) with the bore surface, or by improving the design of the barrel which, for limitation of space, cannot be discussed here.

It will be evident from the above that the understanding of the thermochemical aspects of gas-metal interactions at the bore surface, study of the behavior of various materials in mixed gaseous environments, similar to those resulting from firing, are very important not only to minimize serious erosion in current, but also in the advanced gun barrels of the future.

Conclusion

Erosion is a highly complex phenomenon which involves the combined interaction of thermal, chemical, metallurgical, and mechanical factors. There are challenging areas in which workers in the field of high temperature, gas-metal reactions can very gainfully contribute to understanding the mechanisms, as well as the effective control of erosion.

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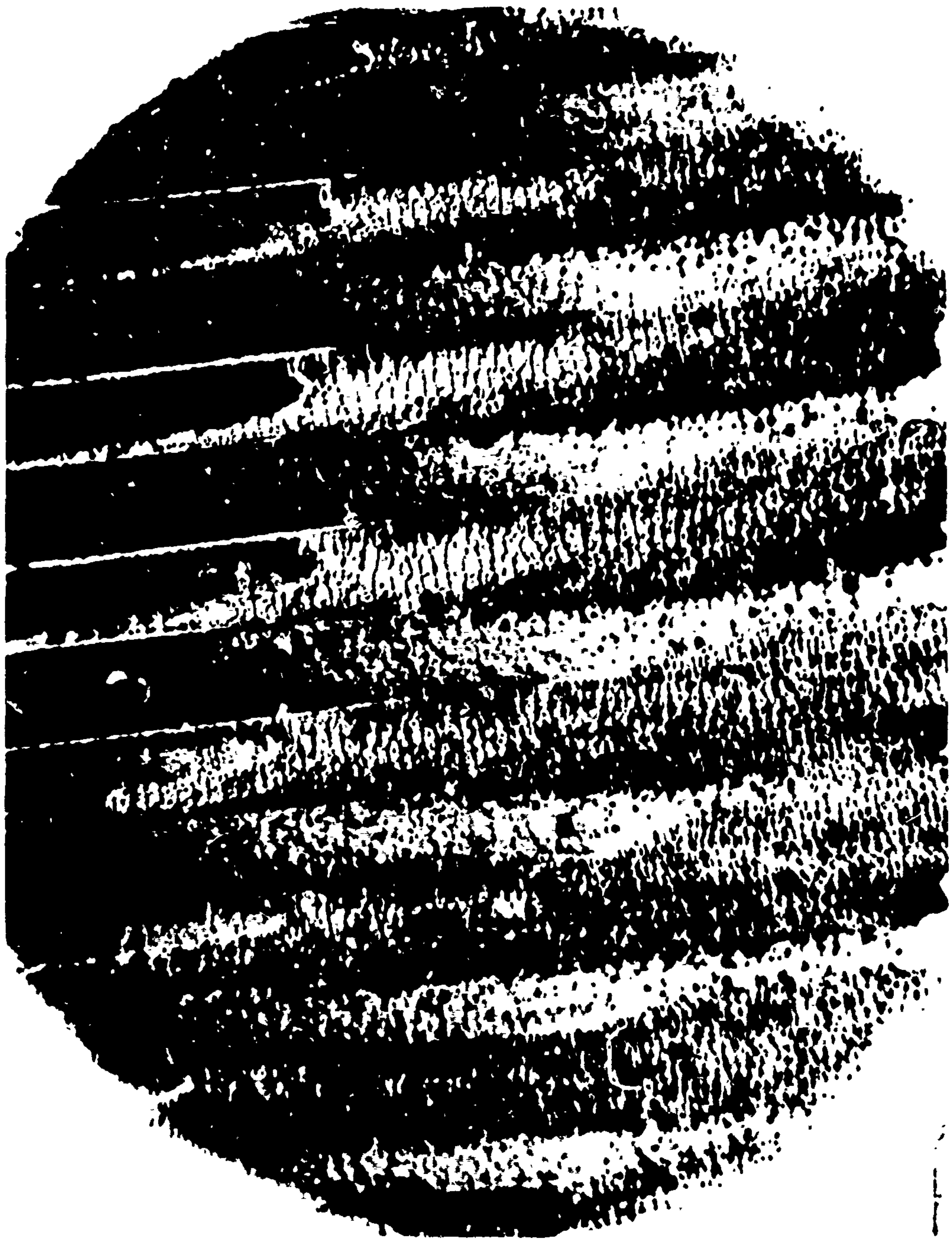


Figure 1. A View of an Eroded 90mm Tube Showing Condition of Rifling at 6 o'clock, after Firing 3370 Rounds.

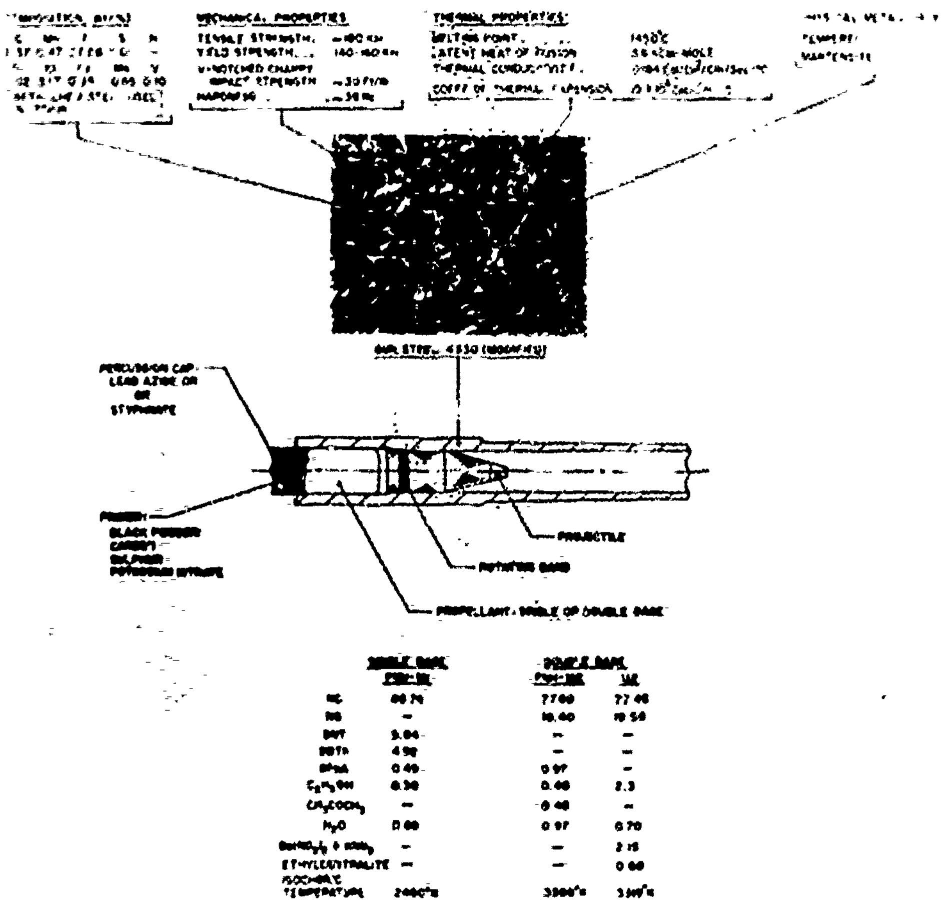


Figure 2. Major Elements Involved in the Process of Erosion.

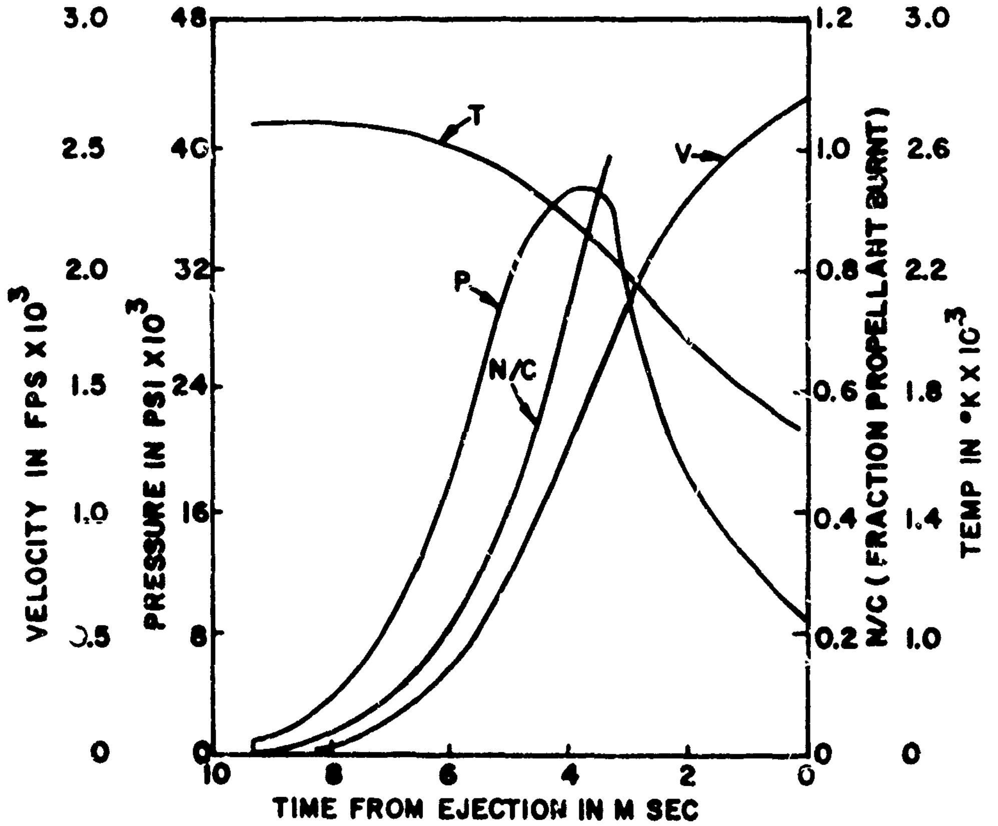


Figure 3. Theoretical Ballistic Curves for 3" Gun (Cardrock Range).

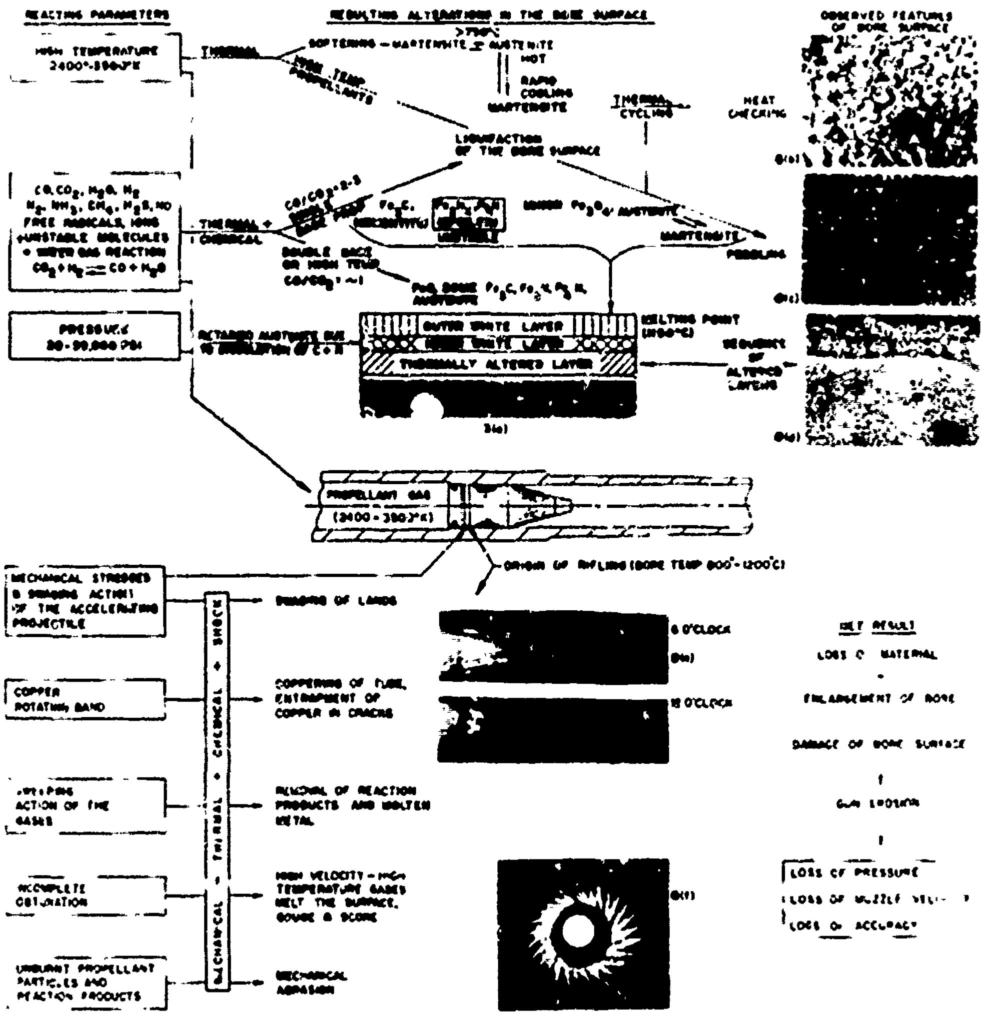
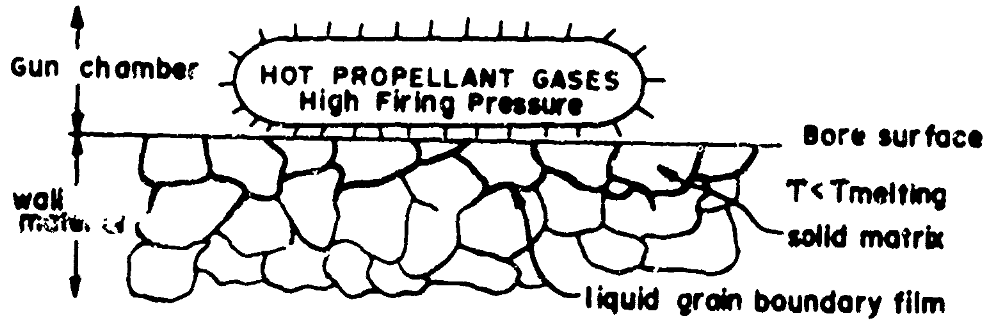


Figure 4. Summary of the Processes Leading to the Erosion of a Gun Tube at the Origin of Rifling.



(a)

(b)

Figure 5. Showing the Liquation of the Grain Boundaries of the Steel at the Bore Surface. (a) Schematic Representation. (b) Observed Liquation in M60 Barrel.

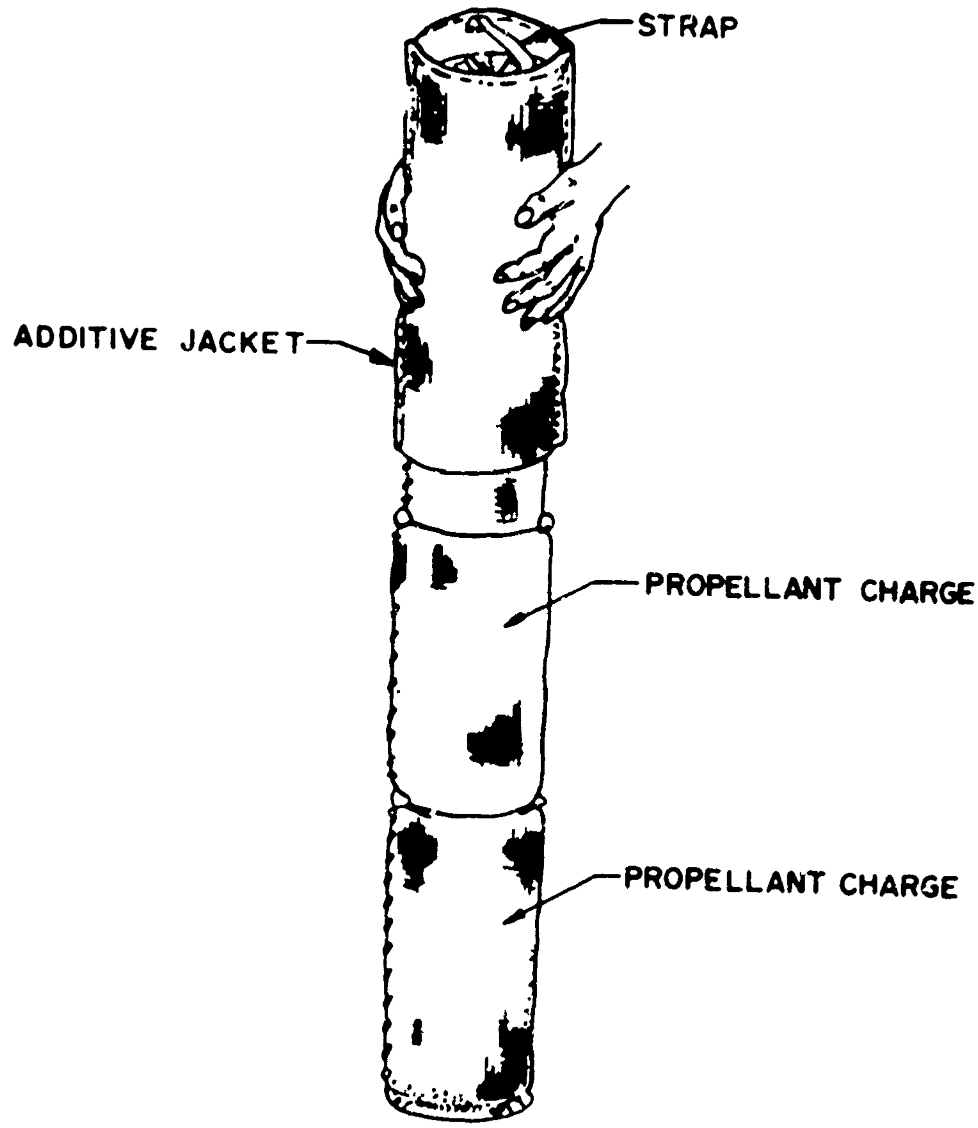
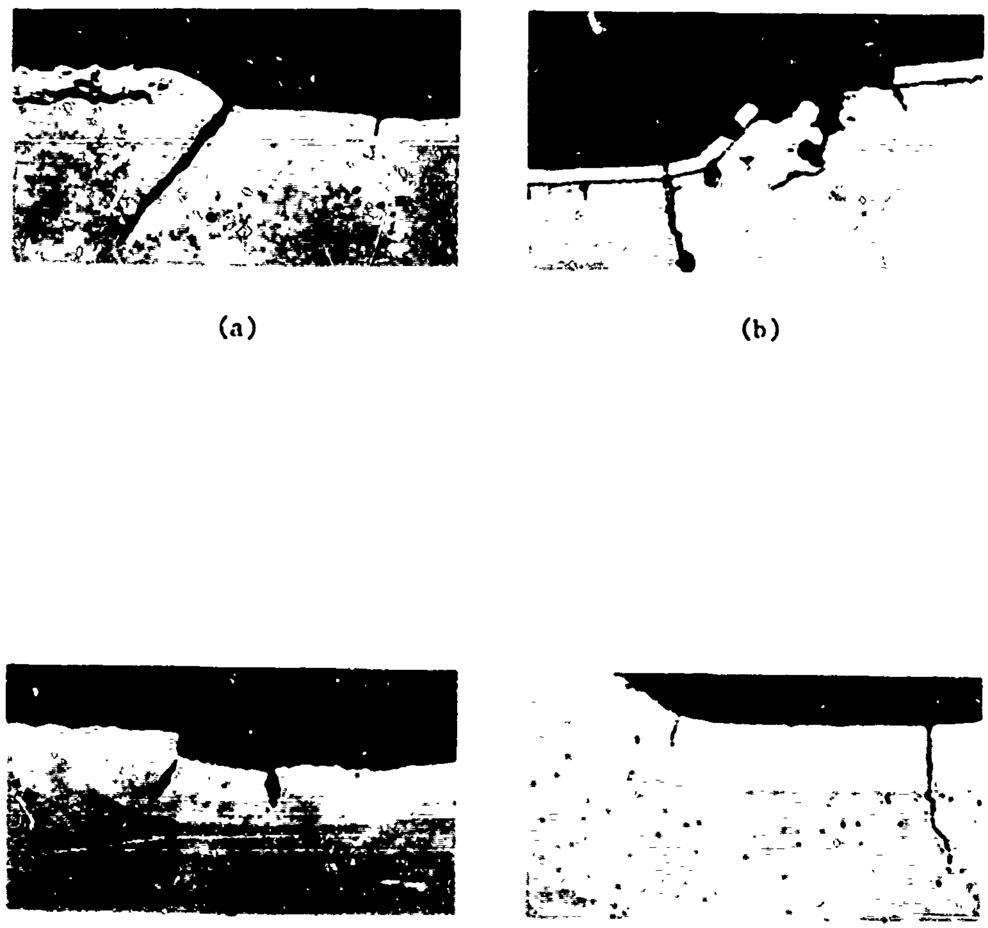


Figure 6. A View of a TiO_2-Wax Additive Jacket.



(a) (b) (c) (d)

Figure 7. Showing the influence of Co-Al_2O_3 coating on the bore surface of a 7.62mm rifle after firing 3500 rounds.
(a) Uncoated tube. (b) Coated with chromium. (c) Coated with Co-Al_2O_3 (2%). (d) Coated with Co-Al_2O_3 (3-4%).

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