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LASER PULSE HEATING OF GUN BORE COATINGS

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13. ABSTRACT *(Maximum 200 words)*

The authors have developed laser pulse heating as a tool for studying erosion processes at gun bore surfaces and for evaluating candidate coatings for bore protection. During firing, the bore coating and steel substrate experience thermal shock from rapid heating and cooling. Thermal pulse durations are in the millisecond range. Despite the short thermal pulse durations, severe coating and substrate degradation processes can occur; these include melting, gas/metal reactions, metallurgical transformations, interface reactions, transformational stresses, and thermal stresses. The degradation processes lead to coating cracking and spallation, which, in turn, allow erosion of the vulnerable underlying steel. Gas/metal interactions may also enhance fracture propagation in the steel. Laser pulse heating is particularly convenient for performing multiple tests on coupon specimens for early evaluations of candidate bore coatings. This allows initial screening of candidate coatings without the difficulty and expense of testing in an actual gun or in a vented combustor.

Laser pulse heating has been applied to gun steel that was electroplated with high-contractile chromium, which is the conventional coating for gun bores. Laser pulse heating has also been applied to low-contractile electroplated chromium and bare steel to provide baseline information. In the present laser pulse heating experiments, samples were repeatedly pulse heated to simulate the effects of multiple gun firings. The samples were then sectioned through the pulse-heated areas and examined to assess the resulting degradation. The results validate the approach. Laser pulse heating reproduces the many features of thermal damage from actual gun firing: recrystallization and grain growth in the chromium, development of major cracks in the chromium, a heat-affected zone in the substrate steel, interface degradation, white layer formation (carburization and/or nitriding), and gray layer formation (rapid oxidation) in the steel.

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INTRODUCTION

Laser pulse heating was evaluated as a method to simulate thermal shock loading on gun bore surfaces during firing. The aim is to establish a convenient tool to obtain more information about the erosion process and to screen prospective bore coatings. At present, many details of the erosion process on gun bore surfaces remain poorly understood. The major contributors to erosion damage include thermal effects, chemical attack by propellant gases, mechanical wear from projectile passage, and mechanical loading from gas pressurization. Gun bore surfaces are typically subjected to short (5 to 10 milliseconds) pulses of high thermal energy during firing of a round. Included among the deleterious thermal effects are melting, metallurgical transformations, thermal and transformational stresses, and surface cracking.

Bore surfaces are often electroplated with high-contractile (HC) chromium to enhance resistance to erosion. The terms high-contractile and low-contractile (LC) refer to the differences in shrinkage and cracking during deposition and annealing of HC and LC chromium electrodeposits. Low-contractile chromium electroplated coatings were recently developed for large caliber gun bores in order to exploit benefits of coatings with lower crack densities. Current efforts are also underway in developing alternatives to chromium (e.g., magnetron-sputtered tantalum).

As with electrodeposited chromium, candidate bore coatings are generally prepared under nonequilibrium conditions, so their microstructures are metastable, and one cannot generally predict the effects of firing on such coatings. Further, their heat transport properties are expected to deviate substantially from handbook bulk properties so that their ability to protect the substrate is not easily predicted. Laser pulse heating can conveniently provide this kind of information (e.g., evolution of metallurgical changes, cracking with number of pulses and pulse energy, and depth of heat-affected zones). For recent comprehensive reviews of the application of lasers to surface engineering, see References 1 and 2.

Thermal Shock Effects in Chromium

There is extensive experience with gun bore protective coatings including HC and LC chromium (refs 3-5). The most detailed compilation of this experience remains the 1946 National Defense Research Committee Report entitled, "Hypervelocity Guns and the Control of Gun Erosion" (ref 4).

A recent survey study of damage initiation in HC and LC chromium plated gun bore surfaces (ref 6) showed that damage to the steel substrate begins at the tips of chromium cracks with propellant gas/metal reactions. The reaction products appear as gray layers or gray zones in the steel. These layers are iron oxide, iron sulfide, or mixtures of the two. Wherever there is a heat-affected zone, the well-known white layer (ref 3) forms in the steel adjacent to the gray layer, indicating that carburization and nitriding occur simultaneously with the oxidation processes.

High-contractile chromium is significantly more cracked than LC chromium after firing (refs 4,6). For HC chromium, the contraction process causes cracking in the chromium during deposition and there is further contraction during the subsequent 200°C anneal to drive out codeposited hydrogen. By contrast, LC chromium remains uncracked until firing occurs. An unresolved question is whether the time at temperature during firing is sufficient to allow chromium contraction or whether thermal shock alone is operative during firing. Another question is whether the thermal shock process alone, i.e., without firing stresses, can fracture the steel substrate. Laser pulse heating was used to address such issues.

Thermal Shock Effects on Uncoated Gun Steel

Laser pulse heating was also applied to uncoated steel specimens to determine the effects of cyclic thermal pulsing on steel and to simulate the effects of repeated firing at the chromium crack tips and in areas where the chromium coating has spalled off.

EXPERIMENTAL METHODS

Laser Pulse Heating Apparatus

Radiation of wavelength 1064 nanometers from a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser is delivered to the test specimen surface in laboratory air. A lens focuses the light from the laser rod into a 10-meter, coiled length of all-silica optical fiber with core diameter of 600 micrometers, cladding diameter of 720 micrometers, and numerical aperture of 0.20. An optical fiber is used both for convenience and for assurance of a uniform energy distribution at the sample surface. Lenses are used at the output of the fiber to form a magnified image of the end face of the optical fiber on the specimen surface. Thus, the spatial distribution of energy at the specimen surface is approximately uniform over a circular spot with a diameter that depends upon the diameter of the optical fiber core and the magnification of the output optics.

The pulse duration is 5 milliseconds (at half maximum), and the spot diameter at the specimen surface is typically 2.6 millimeters. Since the coatings are typically only 0.1-mm thick, a large portion of the heated area duplicates the essentially one-dimensional heat flow through the coating at the bore surface.

For metal coatings, a significant portion of the laser energy is reflected rather than absorbed. Surface roughness, surface oxidation, and changes in roughness and oxidation during laser irradiation are key factors in determining the amount of energy absorbed. In order to permit meaningful comparisons among various coating systems, it is important to quantify the energy absorbed. In most of the specimens in the present study, this absorbed energy was measured calorimetrically. In this method, a thermocouple is attached to the back surface of the thermally insulated specimen. Typically, the test specimen is about 2.5-millimeters thick and cut to a square 6-millimeters on edge. The absorbed energy for each pulse was maintained at roughly 1 J/mm^2, which is representative of the thermal input into the bore with conventional high-temperature propellants. The size of the specimen was dictated by the constraints of the energy absorption measurement. Conveniently, up to four experimental spots can fit on a single specimen. No overlapping effects are observed. The repetition rate is low, typically less than one shot per minute, so that specimen heating during a series of pulses is only several degrees.

Specimens and Analysis

The substrates for chromium electrodeposition and planar sputtered tantalum are 2.5 x 12.5 x 0.25-cm ASTM A723 (gun steel) steel plates in the quenched and tempered state. Specimens for the laser pulsing were cut from these plates. The electrodeposited specimens were generally given a 200°C anneal to drive out codeposited hydrogen.

Analyses methods included scanning electron microscopy (SEM), electron microprobe analysis, energy dispersive spectroscopy, wavelength dispersive spectrometry, and atomic force microscopy (AFM).

RESULTS AND DISCUSSION

HC and LC Chromium

Figures 1 and 2 are reproduced from Cote et al. (ref 7). Figure 1 is an optical micrograph of a cross section of HC chromium electrodeposited on a steel substrate and subjected to 20 laser pulses. The laser-pulsed specimen exhibits all the features of a fired chromium-plated gun bore section as shown in the Figure 2 micrograph from a 120-mm gun tube that had fired approximately 80 experimental rounds and 225 conventional rounds (ref 6). The features include recrystallization and grain growth in the chromium coating, deep cracks in the chromium, a heat-affected zone (transformation to untempered martensite) in the steel, and corrosion attack (iron oxide) at the tips of the chromium cracks that reach the substrate. The surface and embedded cracks in the chromium are present before firing or laser pulsing.

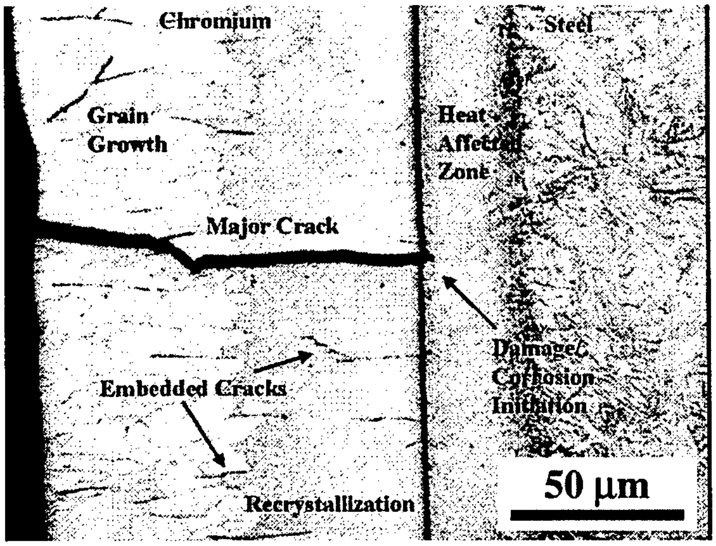

Figure 1. Chromium plated gun steel irradiated with 20 laser pulses producing chromium recrystallation, grain growth and cracking, damage initiation at the tip of the chromium cracks, and a heat-affected zone in the steel.

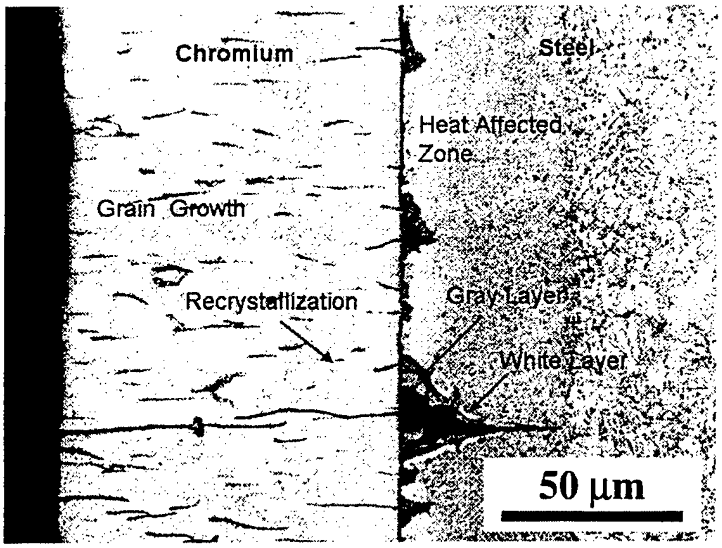

Figure 2. Effects of 80 high-temperature rounds and 220 conventional rounds in a 120-mm gun, similar to the laser effects shown in Figure 1.

Experiments were also conducted to compare the development of cracks on HC and LC chromium specimens after 1, 5, and 20 laser pulses. The thermal shock cracking in the laser-heated area was found to develop by enlargement of the preexisting surface cracks generated in the specimen during deposition and the subsequent anneal to remove hydrogen. By contrast, the cracks in LC chromium develop by initiation and growth since there are no preexisting cracks. So although the widths of major cracks after 20 pulses are similar for HC and LC, the crack densities are substantially lower in LC than in HC, in good agreement with other data for fired gun tubes (ref 6).

Figure 3 shows one of the deepest damage progressions observed in a series of 20 laser pulse experiments on chromium plated steel. Again, the energy delivered was maintained at approximately 1 J/mm^2. Damage initiation in the steel can be seen at the tip of the chromium crack in the upper left. A large, blunt crack originates from the large chromium crack in the lower left and progresses through most of depth of heat-affected zone in the steel. Blunting is always observed at the chromium crack tips in the laser experiments. Such blunt cracks cannot occur in the hard, brittle, compressively stressed untempered martensite in the heat-affected zone. Since SEM and AFM analyses show only a thin oxide layer around the blunt crack, metal consumption by high-temperature corrosion cannot be a factor. Such blunting can only occur in soft austenite that experiences tensile loading during the initial portion of the quench phase. The hardened, compressively stressed, heat-affected zone forms at the end of the quench, below 280°C for this steel. Transformation hardening by laser pulsing is similar to induction hardening and flame hardening in that it produces compressive stresses in the transformed zones (ref 8).

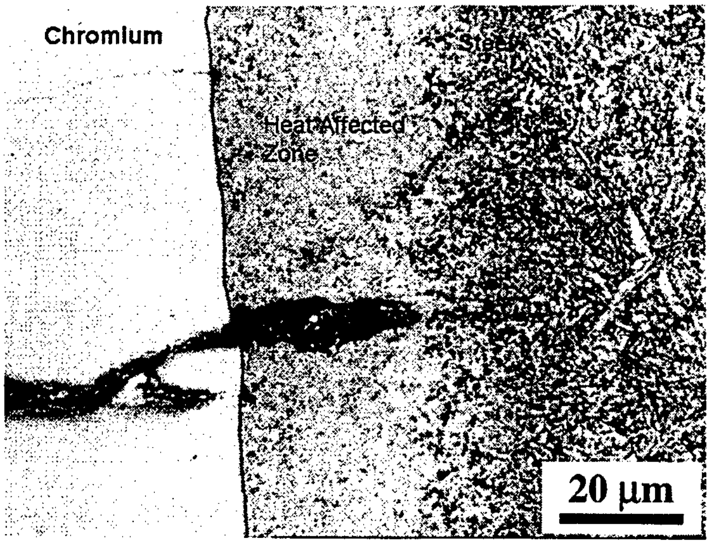

Figure 3. Example of the damage produced in the chromium coating and in the steel substrate by application of 20 laser pulses to chromium plated gun steel. A typical site of damage initiation is shown at the upper left and a large blunt crack in the untempered martensite of the heat-affected zone is shown at the bottom.

The heat-affected zone forms during single pulse, and its depth is not a function of the number of pulses. Thus, the depth of the heat-affected zone can serve as an approximate measure of the depth for which a specific temperature was reached based on the equilibrium phase diagram.

Uncoated Steel

Figure 4 is a micrograph of a cross section of uncoated gun steel that was subjected to 20 laser pulses. A reaction layer (gray layer) is formed on the surface as a result of rapid oxidation of the unprotected steel. A thinner layer is observed after only five pulses. This reaction layer is necessarily the same as the reaction product that forms at the chromium crack tips in plated specimens as shown in Figure 2. Wavelength dispersive spectrometry confirmed the FeO composition in all three cases. An inspection of the surface shown at higher magnification reveals that the oxide layer melted during laser pulsing. This is consistent with the low melting temperature of FeO (1371°C). There was no melting of the steel in this case. FeO is unstable at room temperature, so the presence of this structure in the laser-pulsed specimens (and in gun tubes) is a result of the quench process.

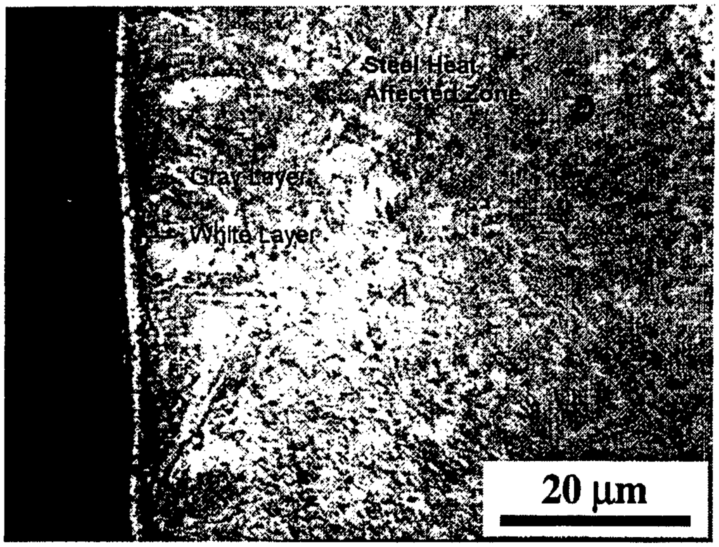

Figure 4. Formation of gray layers and white layers by laser pulsing of an uncoated steel surface. Similar features are seen in fired tubes (Figure 2).

The white layer that forms beneath the gray layer may be a result of nitriding. Similar nitriding effects in air were reported recently with excimer-laser pulsing (ref 10). The white layer that forms in gun tubes (e.g., Figure 2) is well-characterized and consists of carbon- and nitrogen-stabilized austenite (austenite hardened with nitrides and carbides) (refs 3,4).

In contrast to the plated specimens, no pitting or formation of other crack initiation sites in the steel occurs after 20 pulses in the unplated specimens. Thus, the cost for the overall protection offered by chromium plating is an acceleration of localized damage to the steel at the chromium crack tips.

Figure 5 illustrates an example of surface melting occurring in uncoated steel as a result of higher laser input energy. The evidence for melting is the cellular microstructure that developed throughout the approximately 20-micron thick molten layer. The cellular pattern develops as a result of microsegregation of the steel constituents during the solidification process. The significance of this micrograph is that while surface melting is the most severe erosion mechanism in gun bores, molten layers are generally not observed because they are wiped away by high-pressure gases.

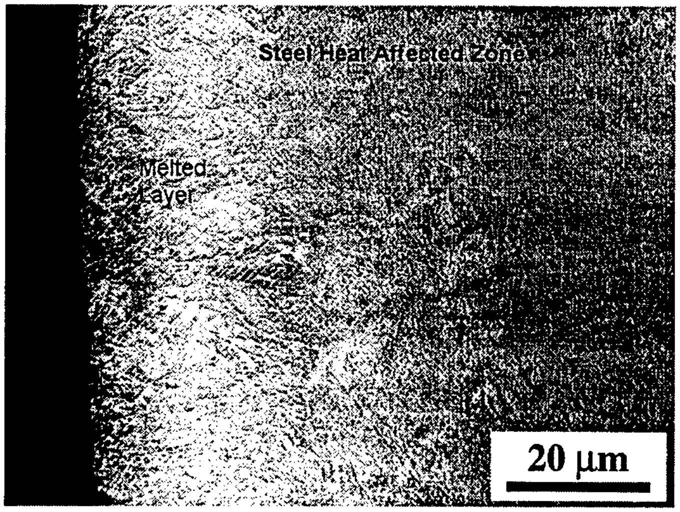

Figure 5. Result of application of 20 higher energy pulses that produced a molten layer at the surface of an uncoated steel specimen. Such melting produces the most dramatic erosion effects. Note the cellular structure of the melted and resolidified steel.

Figure 6 shows a chromium/steel interdiffusion zone at the interface after 20 laser pulses. In the present work, experiments to produce interdiffusion in similar specimens by annealing show a tendency for interfacial failure by development of Kirkendall porosity (ref 9). Similar features are found in fired guns, such as the one shown in Figure 2. There is a tendency for coating spallation in fired guns after exposure to high-temperature rounds. The fact that this tendency persists, despite interdiffusion, suggests interface degradation via the Kirkendall effect. The clear demonstration of interdiffusion in Figure 6 shows that laser pulse heating can be used to quantify these processes.

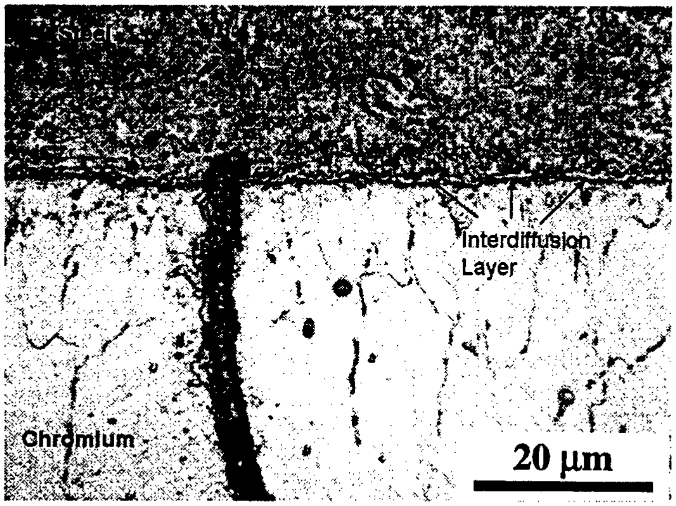

Figure 6. Formation of chromium/steel interdiffusion layer after only 20 laser pulses. Similar effects are seen in fired specimens whenever a heat-affected zone forms in the steel. These results demonstrate that laser pulse heating offers a convenient means to study interface degradation in gun bore coatings.

For completeness, it should be pointed out that in these investigations, only damage initiation sites in fired gun tubes (e.g., Figure 2) were examined because of the focus on initiation processes. The specimens often exhibit cracks that had progressed deep into the steel, well beyond the compressively stressed, heat-affected zone. In fired gun tubes, with much higher numbers of rounds than in the laser pulse experiments, it is likely that mechanical fatigue and thermal fatigue play a role in the development of deep cracks. The possibility also exists that environmental effects, such as hydrogen embrittlement (ref 11), are present in such cases.

SUMMARY

Laser pulse heating was shown to reproduce the main features of the damage process experienced at the bore surface of fired guns, including melting, formation of gray and white layers, recrystallization, grain growth and fracture of the chromium, formation a steel heat-affected zone, and formation of an interface reaction zone. The present results offer fresh insights into issues relating to bore coating degradation as a result of severe thermal cycling and illustrate the broad range of problem areas relating to bore protective coatings that can be explored with laser pulse heating.

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