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Customer Overview of Pulsed Laser Heating for Evaluation of Gun Bore Materials

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Abstract

Pulsed laser heating (PLH) has been shown to be a convenient method to reproduce the transient heating and thermomechanical effects that occur at the bore of large and medium caliber guns during firing. Hence, PLH has been used not only to gain insight into the erosion mechanisms that take place during firing, but to evaluate potential candidate bore materials and coatings.[1-5]

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Experimental Details

In our PLH testing, 1064-nm wavelength light from a multimode neodymium-doped yttrium aluminum garnet (Nd:YAG) laser is delivered to the test specimen surface as shown schematically in the figure below. Laser pulse duration can be varied from 0.1 to 10 ms. The instantaneous power is approximately constant over the duration of the pulse. A lens focuses the light from the laser rod into a 10 m coiled length of all-silica optical fiber with core diameter of 800 μm. An output lens assembly projects an image of the end-face of the optical fiber onto a 2 to 3 mm diameter spot on the specimen surface. An optical fiber is used both for convenience and to help assure a uniform distribution of energy over a well-defined circular spot at the specimen surface.

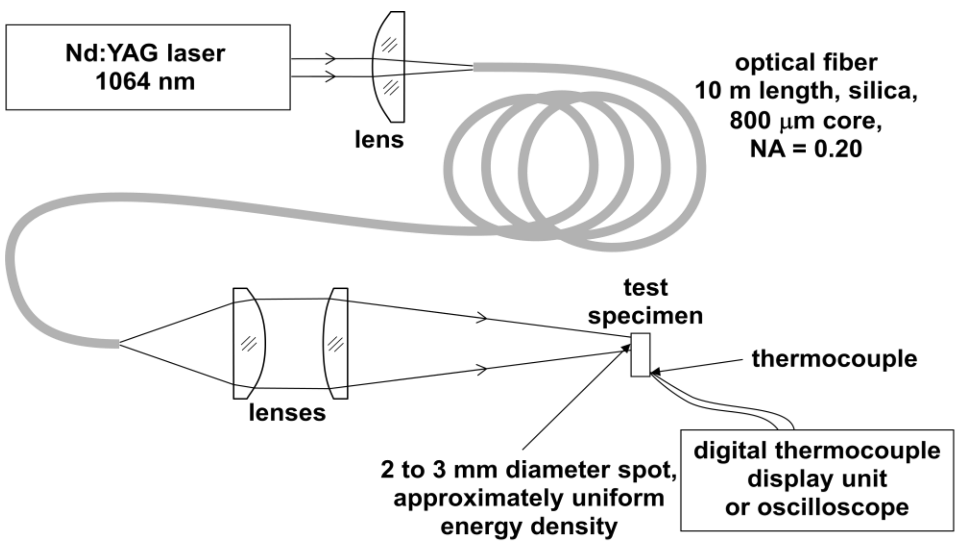

Figure 1: Schematic of pulsed laser heating system.

In most cases, the depth of the volume with high temperatures and high thermal gradients is typically less than 0.2 mm. Hence the heat flux for most of the heated area can be assumed to be approximately one-dimensional and normal to the surface.

A significant portion of the incident laser energy is reflected rather than absorbed, depending on surface conditions such as roughness and the presence of oxides. (Reflectance is the fraction of incident energy reflected; absorptance is the fraction of incident energy absorbed. For opaque samples, the reflectance plus the absorptance equals one.) The actual reflectance is generally unknown and will tend to change as the surface is heated and oxides develop. Therefore, a thermocouple is spot welded to the opposite face of the sample to record the overall temperature increase of the sample after the pulse is absorbed. A simple calorimetric calculation gives the total energy actually absorbed by the sample for each pulse. With knowledge of the spot diameter, and assuming uniform energy absorption over the spot, one can then determine the absorbed fluence (J/mm^2), a quantity of fundamental importance for this method. The use of a calorimetric method for determining the absorbed energy does, however, limit the size of the specimen. Specimen dimensions of 6 mm x 6 mm x 2.5 mm usually work quite well.

With many materials, there can be variations in reflectance over the surface that lead to nonuniform heating within the laser heated spot despite the incident energy being uniform. To compound the problem, areas that absorb more energy get hotter and tend to build up a heavier oxide, and areas with a heavier oxide tend to absorb more light energy. Hence, any nonuniformity in heating often leads to greater and greater nonuniformity as repeated laser pulses are applied. Often the nonuniformity of heating becomes so extreme as to render the method useless: energy absorption is so nonuniform that no reliable estimate can be made of the absorbed fluence at any particular point.

To correct this problem, we have taken to applying either a coating of ink from a permanent marker or colloidal graphite suspended in isopropyl alcohol before each laser shot. We then wipe the sample with isopropyl alcohol and a cotton swab after each pulse and apply a fresh coating of ink or graphite for the next pulse. Although this puts an unknown layer of carbon-based material on the surface, for most fairly inert coatings it does not affect the thermomechanical effects below the immediate surface, which are of primary interest.

The ink and graphite coatings tend to homogenize the absorption of laser energy on the surface. In addition, they also increase the absorptance of the surface. For highly reflective metallic materials, this can be convenient since it can sometimes be difficult or impossible to increase the laser energy enough to achieve the desired absorbed energy on such materials.

In a typical experiment, we are trying to heat a sample for a certain number of pulses, with each pulse having a certain duration and a certain desired absorbed fluence. Since the reflectance is generally unknown, we are presented with a dilemma regarding the incident laser energy to use. Typically, for the first two or three pulses, we overestimate the absorptance of the sample and use a laser energy that is too low to achieve the desired absorbed fluence. Each of these lower energy pulses, however, gives us an estimate of the absorptance and an idea how the absorptance is changing with repeated pulsing and increasing laser energy. Nevertheless, there is a certain amount of uncertainty and judicious guesswork involved in predicting the best incident laser energy for each pulse, since we only know the absorptance for previous pulses. The absorptance of most materials coated with permanent marker ink or graphite tends to increase with repeated pulsing and eventually stabilize to a fairly steady value. We usually err on the side of hitting the sample with too low an energy. When the calculated energy absorbed is 95% of the target energy or greater, we usually count that pulse toward the number of pulses required for the test. Pulses of lower energy are noted but not counted toward the required number of pulses. Ideally, there are no pulses greater than about 105% of the target energy.

Although the laser is capable of being fired in fairly rapid succession (every few seconds or so), we typically do not do this because of the above issues. It typically takes at least 10 to 15 seconds for the sample to come to thermal equilibrium allowing for the temperature measurement that determines the total heat absorbed. Generally, to avoid the sample heating up over the course of multiple pulses, we allow the sample to cool to near room temperature before applying the next pulse.

Modeling and Determination of Laser Parameters

The purpose of pulsed laser heating is generally to duplicate the transient heating that the test material would experience if it were used at the bore of a gun. Hence, it is first necessary to know, or at least estimate, what sort of heating would occur at the bore surface, which depends on such factors as gun bore geometry, specific location within the bore, projectile and propellant, and the thermal properties of the gun bore materials. Ideally, well validated interior ballistics modeling has been carried out (typically with NOVA) to provide time-dependent gas temperature and convective heat transfer coefficient (aka convection coefficient) at various bore locations.

Given the time-dependent gas temperature and convection coefficient at a particular location (as found above), we would then use a one-dimensional finite-difference heat transfer code to determine the actual heat flux to the bore at that location. For this phase of modeling, we would need to know the following properties of the bore material or coating: (a) thermal conductivity at room temperature and elevated temperatures, (b) specific heat at room temperature and elevated temperatures, and (c) density. Optionally, a more sophisticated model could be run in finite-element analysis software if one is concerned with the details of heating around rifling.

If one is concerned with the additional heating due to rapid, multiple-round firing, we would model the heat transfer with finite-element analysis software or an in-house axisymmetric finite-difference code. The bore temperature in rapid fire is a sequence of sharp pulses superimposed on a gradually rising baseline. We would not attempt to duplicate the rapid fire scenario itself with pulsed laser heating. Rather, we would simply attempt to achieve with single-shot pulses the peak temperature seen in rapid fire (the last pulse of the sequence).

The results of this step of modeling include plots of (a) heat flux (W/mm^2) vs. time and (b) temperature vs. time at the surface and at particular depths (including the coating-steel interface).

The next step is to determine the appropriate laser pulse parameters that would duplicate the convective heating results. This is not necessarily straightforward because the time dependence of the laser pulse is approximately a square wave and the heat flux from the convection model is not. The only two laser parameters to control are pulse duration and absorbed fluence (J/mm^2). To explore the effects of different combinations of duration and absorbed fluence, we would model the heat transfer due to laser heating with a one-dimensional finite-difference code and plot the temperature vs. time at the surface and at particular depths for various sets of laser parameters.

There are a number of possible approaches to choosing an appropriate combination of pulse duration and absorbed fluence, including:

(a) Determine the full-width-half-max duration and the total energy fluence from the convective heat flux curve. Then set the laser duration and fluence to match. This will provide an overall similar thermomechanical shock (to cause cracking) as convective heating, but may give peak surface or interface temperatures quite different from those from convective heating.

(a) Set the laser fluence to match the convective heating fluence, and adjust the duration of the laser pulse until you get the same peak surface temperature that was reached for convective heating.

(b) Run trial-and-error iterations to determine the laser duration and fluence that would yield the same peak surface temperature and coating-steel interface temperature as for convective heating.

It may be best to apply more than one pulsed laser heating protocol after examining a number of different approaches.

Post-Heating Evaluation

After a particular pulsed laser heating protocol is applied, the sample would be examined to determine what effects laser heating had on the materials. Possible effects include cracking (due to thermal shock), delamination of coatings, melting, recrystallization, and formation of a heat-affected zone in the substrate steel. The heated surface can be examined under a microscope. The sample would then be cut, mounted, and polished for metallographic examination of the cross section of the heated spot. This examination usually yields the most useful information.

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