Security study of laser measuring methods on high explosives

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Abstract: Interaction activities between the laser photons and the molecular of high explosives were described; the threshold of the laser beams’ power on the surface of the high explosives is achieved limiting the interaction probability between molecules of the high explosive and the photons, their changes of properties with the mathematical norm commonly used in engineering. Research confirm the security of common active optical measuring methods on high explosives, and prove the capability of their wide applications in measuring the properties and state characteristics of high explosives.

1. Introduction

Most of the propelling energy of the modern weapons is provided by the high explosives; therefore, the physical and chemical properties including the state of the high explosives have great influences on the managements and storage of such weapons. With demands to ensure the uniform state of the loaded high explosive, maintenance of its mechanical capability and the stability of the chemical components, etc. called a variety of measuring methods based on the acoustics, electrics and other theories keeping up with the development of science and technology. Being an important active method of the optical measuring methods, the laser measuring method provides a highly precise and automated ways to verify the state and properties of the high explosives. Lasers are a kind of pure light with high coherence, orientation and luminance; therefore, it can be used in measuring the existence of the explosives, the size of the loading surface \cite{1}, loading displacements, characteristics of aging and damage near the surface \cite{2}, etc.. However, the lasers are composed by energy photons and the high explosives are sensitive to thermal loads; this leads the lasers to be treated as ground weapons detonating the high explosives in coming weapons, or as spatial orientated weapons to attack the satellites and block the missiles \cite{3} in military applications, it was seldom to be used in measuring the state and properties of high explosives \cite{4}, as well as the radiation detection methods \cite{5}.

According to the interaction activities between the molecule of the high explosives and the photons, the paper calculated the interaction probability of a single molecular of high explosives when the laser beams’ power varied and thermal field of the radiated areas was simulated. Aiming to prove the security of its usage for measuring the state and properties of the high explosives, the paper obtained the limit magnitude of the laser beams’ power based on the mathematical norm commonly used in engineering and the time-temperature superposition principle.
2. Theoretical Background
Causing that some of the energy of the photons is absorbed and the photons vanish or change, some photons are scattered by the molecules of matters, the intensity of the photon’s flows will be decreased when it is penetrating matters. The energy of the laser beams is absorbed by the molecules and changed to another form: kinetic energy. Being scattered by the molecules, the motion directions of the photons in the laser beams are changed and some of their energy is transferred to the molecules collided.

Interaction activities between the photons and matters. The main interaction activities of the photons with matters are the Photon-electric Effect, the Compton Effect, the Pair Production Effect and the Photoionization Effect. The Rayleigh scattering effect should be considered when the energy of the photons is quite low, furthermore, other activities such as photonuclear reactions and nuclear resonance reactions happens with little probability.

When the photons interact with the constrained electrons around the nucleus, the total energy of the photons is transferred to some constrained electrons, the electrons emit while the photons vanished, this phenomenon is called the Photon-electric Effect, the emitted electrons are called photoelectrons. The atoms absorb the energy; part of them acts as the ionization energy the electrons needed to escape and part of them acts as kinetic energy of the photoelectrons. When the energy of the photons is large, the photons collide non-elastically with the electrons around the nucleus. Part of the energy of the photons is transferred to the electrons and they recoil. Homogenously, the energy of the photons as well as their motion directions change; this phenomenon is called the Compton Effect. As the energy being increased, the photons will change to a pair of electrons carrying positive and negative charge respectively in the coulomb fields around the nucleus; this is called the Pair Production Effect. The neutral atoms are ionized to electrons and positive ions when the energy of the photons is larger than the ionization energy threshold of the gaseous molecules, such a phenomenon is called the Photoionization Effect.

The interaction probability between the photons and the matters is quantified by cross sections, which is defined as the probability of a single target nucleus in the unit area reacting with a particle in given energy and vertical directions. The unit of the cross sections is barns, equaling to $10^{-24}\text{cm}^2$. Each reaction channel has its own cross sections, e.g. the photon-electrical cross sections $\sigma_{ph}$, the coherent scattering cross sections $\sigma_{cs}$, the incoherent cross sections $\sigma_{is}$, and the pair production cross sections $\sigma_{pp}$, etc.

High Explosives. The high explosives are a kind of material composed of the Carbon, hydrogen, nitrogen and oxygen elements with high-energy density. The modern typical high explosives are mainly composited by HMX (or called Octogen; the molecular formula is $(\text{CH}_2)_4(\text{NNO}_2)_4$), They are composed of insensitive or plasticized materials such as TATB, BDNPA, etc. (The general high explosives, and their constitutions are listed in Table. 1).

| High explosives | Molecular formula | constitutions |
|-----------------|-------------------|---------------|
| HMX             | 296.2             | 4 H 8 N 8 O   |
| TATB            | 258.2             | 6 H 6 N 6 O   |
| TNT             | 227.1             | 7 H 5 N 6 O   |
| HNS             | 450.3             | 14 H 6 N 6 O  |

3. Security Analysis
Application security of the high explosives has been paid great attention. In addition to the effect on human bodies, the security that the high explosives is blocked by alloys in weapons engineering is researched in detail and the limit of the laser beams’ power was also made clear. Due to some unknown problems, little efforts were down to monitor the change of the high explosives when they were exposed to laser beams with moderate power.

The carbon, hydrogen, nitrogen and oxygen elements that high explosives compose of interact with the photons and the Photon-electric Effect, scattering or photoionization effect takes place, absorbing photons’ energy and producing positive holes or electrons (or pairs of electrons), such effects can break the chemical bonds of high explosives and speed up the thermal decomposition. Therefore, the
measuring security can be evaluated by the microscopic interaction probability of a single molecular and the increased temperature macroscopically when the high explosives are radiated by lasers.

The Interaction Probability of a Single Molecular of high explosives with Laser Beams. The electrons around the nucleus in the molecule of the high explosives will escape or be excited after they interacted with the photons and thus the molecule change from the original state, the physical and chemical characteristics, to some degree, will change with it. Their interaction activities with photons can break the chemical bonds and speed up the thermal decomposition process. Therefore, in microscopic view, the interaction probability of the molecular of the high explosives with the photons should be small enough to remain their macroscopic properties.

Illustrating with HMX, the total cross-section of a single HMX molecular is the linear sum of their component elements:

\[ \sigma_t = \sum_i m_i \sigma_{t,i}, \quad \sum_i m_i = 1, \quad \sigma_{t,i} = \sigma_{l,ph} + \sigma_{l,cs} + \sigma_{l,ls} + \sigma_{l,pp} \]  

(1)

Where \( \sigma_t \) is the cross-section of the HMX molecular to photons, \( \sigma_{t,i} \) is the total cross sections of carbon, hydrogen, nitrogen and oxygen, \( m_i \) is the mass percentage. According to the EPDL data and equation (1), the cross sections of hydrogen, nitrogen and oxygen elements based on the energy numbers in the cross section data of carbon element could be interpolated linearly and then the total cross section data of a single molecular of HMX would be obtained (see in Fig. 1).

![HMX-photon total cross sections](image1)

Fig. 1 total cross-section of a single HMX molecular with photons

Supposing the power of the laser beams: \( P=1\, \text{W/m}^2 \), the interaction probability of a single molecular of HMX with photons: \( \eta = N\sigma_t = P\sigma_t/E \) (\( E \): energy of a photon of the laser beams) (see in Fig. 2).

Nowadays, the range of the wavelength of the lasers developed is \( 0.12\, \text{nm} \leq \lambda \leq 3\, \text{mm} \), and the photon energy \( E = h\nu = hc/\lambda \) (\( h \) is the Prandtl number, \( 6.6260693\times10^{-34} \, \text{J} \cdot \text{s} \)), that is: \( 4.136\times10^{-4} \, \text{eV} \leq E \leq 10.339\, \text{keV} \). And the common lasers used in industry are visible, the photon energy: \( 1.6325 \leq E \leq 3.265 \, \text{eV} \). Conclusions could be drawn that:

1. The interaction probability of a single HMX molecular with photons of industrial lasers is quite small, and it rises quickly when the lasers' frequency grown up, the maximum cross section is up to \( 10^7 \) in magnitude. However, the probability goes down when it passes over the maximum with the frequency being increased. The cross section of a single HMX molecular interacting with laser photons decreased steadily and stabilized itself in about \( 10^6 \) barns in magnitude.

2. The interaction probability of HMX molecule is high when it is exposed to industrial lasers with power of \( P=1\, \text{W/m}^2 \), the magnitude varies in \( 10^{-10} \sim 10^{-8} \). According to the mathematical norms in engineering, the interaction probability of a single molecular of HMX with photons is supposed to be less than \( 1\% \), then the exposed power of lasers on the high explosives should be less than \( 10^3\, \text{W/m}^2 \), \( 10^5\, \text{W/m}^2 \) in some cases. The interaction probability decreases when the laser frequency was increased, which means the interaction probability of HMX could be deceased when the laser frequency had been raised while the laser beams power kept unchanged.
Energy Absorption by High Explosives of Lasers. A laser beam is composed of many photons with given energy. Considering the photons are wave-corpuscle duality, the energy transferring procedure can be explained in two ways: the photon energy is transferred to the high explosives while the molecules of high explosives interacting with the photons, or molecule of the high explosives are excited under the electro-magnetic fields produced by the laser photons and then they move faster. The high explosives absorb energy explained from either side of the wave-corpuscle duality of photons.

Supposing the energy absorption ratio of high explosives to lasers is $\eta = 0.3$. According to the thermodynamic principle, the temperature field of the high explosives exposed to laser beams satisfies the flowing equation

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \eta P$$

(2)

Where $\rho$——the density of the high explosive, $c_p$——specific heat, $T$——temperature, $t$——time, $x, y, z$——distance between a random point to the original planes in global coordinates systems, $P$——power of the laser beams.

Thermal simulation analysis could be carried on with the finite element method. (Thermal properties are listed in Tab. 2), the initial temperature $T_0=20^\circ C$ and the conduction coefficient $h=15 W/(m^2K)$ (See Fig. 3 and Fig. 4).

| Tab. 2 | thermal properties of HMX |
|--------|---------------------------|
| Density ($\rho$) | Thermal-conductivity coefficient ($\lambda$) | Specific heat ($c_p$) |
| unit Kg/m$^3$ | W/ (m·K) | J/ (Kg·K) |
| numbers | 1790 | 0.346 | 1050 |

Conclusion can be drawn that: the increased temperature of the high explosives is ignorable when the exposed power of laser beams is quite low, e.g. far less than $10^2 W/m^2$. The increased temperature rises when the power grows up and it is very apparent when the power reached to $10^5 W/m^2$ in magnitude.

It is very important for the high explosives to remain its properties steady causing that they are commonly used in military or vital industry such as aerospace and aviation. Researches demonstrated that properties of high explosives, such as the mass loss due to thermal decomposition, mechanical changes, follow the time-temperature superposition principle, the slight effect of viscoelastic material when the temperature raised is similar to the effect when the strain ratios are reduced. In mathematics, for a random mechanical property $E$, there exists:

$$E(T, t) = E[T_0, t/\alpha(T)]$$

(3)

Where $\alpha_T(T)$ —— the shift factor in given temperature, $t/\alpha_T(T)$ —— the shift time. Shift factors
can be solved by Williams-Landel-Ferry (WLF) equations[6]

\[
\log \alpha_T (T) = - \frac{C_1(T-T_0)}{C_2+(T-T_0)}
\]

(4)

Where \(C_1\), \(C_2\) are constant numbers of given materials, \(T_0\) is chosen as the reference temperature. To some high explosive, researches showed that: (1) the mass loss follows the time-temperature superposition principle and shift factors are \(C_1=-11.9232, C_2=-342.7419\); (2) the extended modulus and extended power follows the time-temperature superposition principle and shift factors are \(C_1=-73.8942, C_2=-426.8054\)[7].

Supposing the properties of high explosives could not change over 5% in given temperature when they were measured with laser beams, that is \(1/\alpha_t(T)\leq 1.05\), then the maximum temperature increased of the high explosives calculated with the shift factors is 0.6080K and 0.1224K respectively, which means the maximum magnitude of lasers power is \(10^5\)W/m² (see Fig. 3).

4. Conclusions and Discussions

Optical measuring methods provide an accurate way to measure the properties and state characteristics of high explosives and it could be upgraded automatically and intelligently. Being an active optical measuring method, the laser measuring method might cause some security problems because the energy of lasers could be absorbed and the high explosives are thermal sensitive. The security problems could be evaluated by means of limiting the interaction probability between the high explosives and the laser photons, or the changes of their properties. Results show that:

(1) The interaction probability of a single molecular of HMX with the laser photons is quite small when the wavelength is in the range of visible lights, and the frequency increases, the probability grows up rapidly to the maximum and then decreases slowly. If the interaction probability is limited to 1‰, the power of the laser beams exposed to the high explosives should not exceed \(10^5\)W/m², in some cases, \(10^7\)W/m² in magnitude.

(2) The energy absorbed by the high explosives could be transferred quickly when the power of the lasers was very small, e.g. when the power was less than \(10^4\)W/m², the increased temperature is not evident. The increased temperature grows up while the power was raised. The temperature change is assignable when the power of laser beams exceeds \(10^5\)W/m² in magnitude. Furthermore, the properties of high explosives change with the temperature, if the property value is not supposed to change exceeded over 5%, the power of the laser beams exposed to the high explosives should be less than \(10^6\)W/m² in magnitude according to the time-temperature superposition principle.

Conclusions were drawn that: (1) it is secure of the high explosives when they are measured by lasers commonly used in industry, the interaction probability with laser photons is quite low and the change of the properties is not remarkable. (2) The power of the laser beams is expected to be less than \(10^5\)W/m² in magnitude to remain the state of the high explosives stabilized when they are measured with active optical measuring methods.

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