Laminated helmet materials characterization by terahertz kinetics spectroscopy

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ABSTRACT

High speed acquisition of reflected terahertz energy constitutes a kinetics spectrum that is an effective tool for layered materials' deformation characterization under ballistic impact. Here we describe utilizing the kinetics spectrum for quantifying a deformation event due to impact in material used for Soldier's helmet. The same technique may be utilized for real-time assessment of trauma by measuring the helmet wore by athletes. The deformation of a laminated material (e.g., a helmet) is dependent on the nature of impact and projectile; thus can uniquely characterize the impact condition leading to a diagnostic procedure based on the energy received by an athlete during an impact. We outline the calibration process for a given material under ballistic impact and then utilize the calibration for extracting physical parameters from the measured kinetics spectrum. Measured kinetics spectra are used to outline the method and rationale for extending the concept to a diagnosis tool. In particular, captured kinetics spectra from multilayered plates subjected to ballistic hit under experimental conditions by high speed digital acquisition system. An algorithm was devised to extract deformation and deformation velocity from which the energy received on the skull was estimated via laws of non-relativistic motion. This energy is assumed to be related to actual injury conditions, thus forming a basis for determining whether the hit would cause concussion, trauma, or stigma. Such quantification may be used for diagnosing a Soldier's trauma condition in the field or that of an athlete's.

Keywords: Terahertz kinetics spectroscopy, laminated material, deformation kinetics, diagnosis of trauma

1. INTRODUCTION

Unlike other form of energy that can be used for probing materials and physiological events, such as, X-ray, UV, Visible, Infrared and ultrasonic, terahertz radiation (T-ray) provides unique advantages in that the T-ray can penetrate through many materials and biological tissue, allowing sub-surface interrogation in a non-destructive and non-invasive fashion. Consequently, T-ray based reflection beam kinetics spectra can produce a clearer picture of the internal layers of composite laminates and their delamination than simple surface measurements. Additionally, a transmitted beam kinetics spectrum may be used to probe any mass loss of the material due to evaporation at impact or mass gain due to sticking of projectile fragments. The real-time kinetic spectrum can be used for computation of force and energy of impact that in turn may be exploited for the evaluation of trauma conditions from the Sturdivan criterion [1]. Currently available technologies offer limited sensitivity to certain important parameters, such as dynamic mass loss that are crucial to fully quantify a ballistic event. Existing methods such as digital image correlation (DIC) [2] suffers from critical limitations because most of them are not able to quantify changes of the internal layers. While X-ray can penetrate, one can only view a snapshot after the event has already taken place (ex-situ); no dynamic, real-time information is available. While DIC offers time-evolution of the deforming surface, is not capable of providing any information regarding interior delamination or change in mass. Moreover, DIC lacks very fine resolution necessary for in-situ inspection of time-dependent changes in materials. Microwave could potentially be used for similar interrogation but lacks sensitivity necessary for probing ballistic events. On the other hand, terahertz kinetics spectroscopy is very effective technique that can address the aforementioned deficiencies by providing information for a more complete characterization of ballistic events. Recently we reported on capturing ballistic kinetics on an Army Research Laboratory's test-bed using a terahertz scanning reflectometer (see ref [3] for details).

In this report we used non-relativistic equation of motion for interpreting the kinetics spectrum for ballistic event characterization of less-than-lethal impact, the so called blunt criterion [1]. The experimental setup was described elsewhere [3]; however, the calibration procedure for quantifying deformation from the kinetics spectra is briefly described below. A live-fire shot on a multi-layered panel has been analyzed in details. We also describe calibration and calculation of mass loss due to ballistic impact. Details of terahertz generation have been reported elsewhere [4].

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Briefly, we have used a dendrimer dipole excitation (DDE) based terahertz source, first proposed in ref. [4] where an electro-optic dendrimer with high second order susceptibility is pumped by a suitable laser system. This mechanism does not require a femto-second pulsed laser; it is capable of generating CW T-Rays with relatively high power (>10 mW). DDE based terahertz system is attractive, because it eliminates the use of a femto-second pulsed laser that makes it cost effective and tunable for both bandwidth and output power.

1.1. Quantitative analysis of a ballistic event

In the case of a Soldier's helmet, an important quantity is the available energy for potential impact to the Soldier's head that may lead to trauma, concussion or other injury. The same principle will also apply for sport helmets with a lesser degree of impact force. Therefore, it is important to quantify the trauma generating energy, E_{tr}. At the point of impact, the kinetic energy, E_K, of the projectile is $E_K = \frac{1}{2} m_P V_P^2$, where, m_P is the mass of the projectile, and V_P is the impact velocity of the projectile. Sturdivan et al. [1] indicated that the physical quantity properly expressing the capacity to do work on tissue and cause damage from blunt impact is the "energy." The authors expressed potential blunt criterions (BC) for the head as a measure to predict head injury from blunt, less-than-lethal projectiles, as

$$BC = ln\left\{\frac{E}{(T*D)}\right\}, \tag{1}$$

where, E is the impact kinetic energy (Joules) of the deformed volume, D is the diameter of the projectile in centimeters, and T is the thickness of the skull in millimeters. One needs to recognize that, as a projectile (e.g., a bullet) impacts the outside of a helmet, the inside of the helmet is deformed inwards, thus imparting energy to the Soldier's head. It is this energy that causes trauma, concussion or other injury; which is less than the impact kinetic energy, E_K, of the projectile on the helmet's outer skin (see Fig. 1). Eq. (2) therefore takes the form,

$$BC = ln\left\{\frac{E_{tr}}{(T*D)}\right\} \tag{2}$$

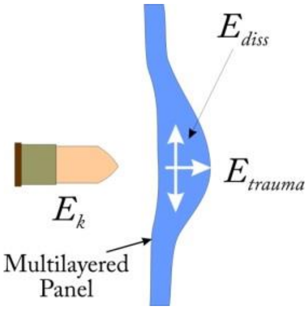

Fig. 1. The incident energy is the sum of trauma-generating energy and dissipated energy: $E_k = E_{tr} + E_{diss}$.

The kinetics spectrum is used to compute the velocity profile from which the deformation propagation velocity for the helmet interior surface is obtained at the maximum deformation, V_{max}. However, since

$$E_{tr} = \frac{1}{2} m_{eff} V_{max}^2 \tag{3}$$

where, m_{eff} is the effective mass of the trauma generating volume, excluding the mass of the bullet. Therefore, to quantify the energy of BC, m_{eff} must be known. But neither DIC nor X-ray can determine m_{eff}, because, while the density may be approximated from the known material properties and the effective area (volume) may be estimated from the post-firing device under test, the effective mass of the trauma-generating volume is still not determined. Since the helmets are made from a multi-layered material, one needs to know the delamination characteristics and the lost mass of material due to impact. Thus, m_{eff} must be determined experimentally. Here we exploit T-Ray's penetration properties through the helmet material to determine any mass loss/gain due to impact. In this case, calibration of material mass as a function of T-Ray transmission energy must be done á priori.

In light of the foregoing, the total energy delivered by the projectile is then comprised of two components: $E_K = E_{tr} + E_{diss}$, where E_{diss} is the energy dissipated by the helmet material (see illustration, Fig. 1). While it can be easily assumed that $E_{diss} = E_K - E_{tr}$, the nature of E_{diss} has some interesting connotations. One may argue that since the helmet is made of a multilayered material, E_{diss} is not likely to be just the dissipated heat energy. It is hypothesized that ballistic impact may generate shock waves [5] which may also contribute to trauma. In either case, the net effect of a ballistic impact, under *BC*, is the trauma generating energy E_{tr}, and thus, E_{tr} is still dependent on m_{eff} which must be measured.

2. EXPERIMENTAL

Fig. 2 shows the experimental setup for real-time in-situ ballistic kinetics spectra measurements. Projectiles (762 rounds and fragment-simulating projectiles) were shot at composite panel targets to demonstrate feasibility of the proposed measurement system. An electro-optic dendrimer based terahertz source was used for the present measurements [4]. The source and the detection units remain stationary and are oriented at angle $\theta = 35°$ but may be oriented at any suitable angle such that the projectile path is clear from entering the instruments (Fig. 2). Under these conditions, as the target moves from its initial position along the x-axis, both θ and the deformation (S) become position dependent; $\theta \rightarrow \theta(x)$ and $S \rightarrow S(x)$. Thus the reflected power is a function of x that can be described by the Fresnel's law of refraction [6].

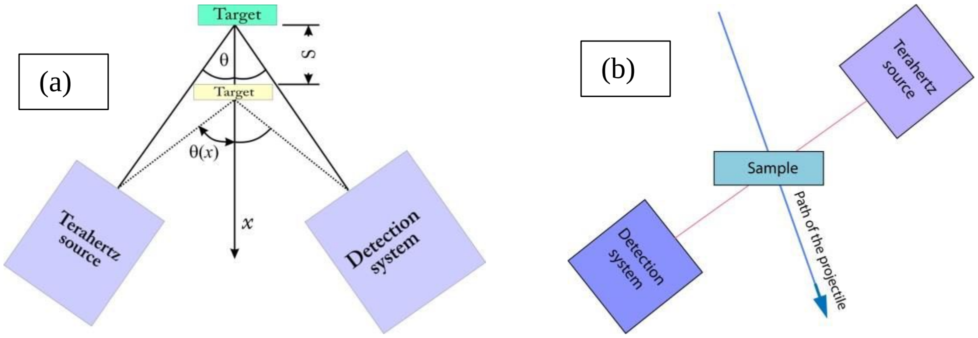

Fig. 2. Experimental setup of TDR. (a) Reflection calibration: the terahertz source and the detection unit remain stationary while the target undergoes sudden deformation by absorbing ballistic impact. The beam from the source is incident at an angle (35°) on the target and reflected back into the detection system. (b) Experimental setup for mass vs. transmission calibration

2.1. Deformation calibration

Deformation calibration involves measuring the reflected energy as a function of known deformation at a given distance and a known angle of incidence. Fig. 3 shows the results for three different materials. Here panels of those materials were mounted on a linear stage that has sub-micron lateral resolution. Since helmet deformation is usually in a few millimeter range under ballistics impacts, calibration was conducted over at 1 mm intervals. However, calibration could have been done at a finer resolution for more sensitive experiments. This calibartion curve may be utilized for reading off the actual deformation under experimental conditions knowing the difference between the initial and final reflected intensities.

2.2. Mass Calibration

The effective mass m_{eff} (Eq. (3) or change in mass) may be read off from the mass vs. transmission calibration. The governing principle here is the Beer-Lambert's law. Ordinarily, the Beer-Lambert's law is used to determine the concentration dependence, *C*, of a solute in a solvent from absorbance (*A*) data: $A = \varepsilon l C$, where l is the path length and ε is the extinction coefficient (or molar absorptivity). However, for a ballistic impact, all material parameters may be assumed fixed, with the path length l being replaced by mass, m, due to delamination. Thus, the transmittance (T) is proportional to the variation in path length, or equivalently, the mass change. Therefore, a priori measurement of $T(t)$

vs. known m can be utilized to compute the change of mass: $T(t) = \varepsilon m\rho$, where, ρ is the density. The mass calibration setup is shown in Fig. 2(b).

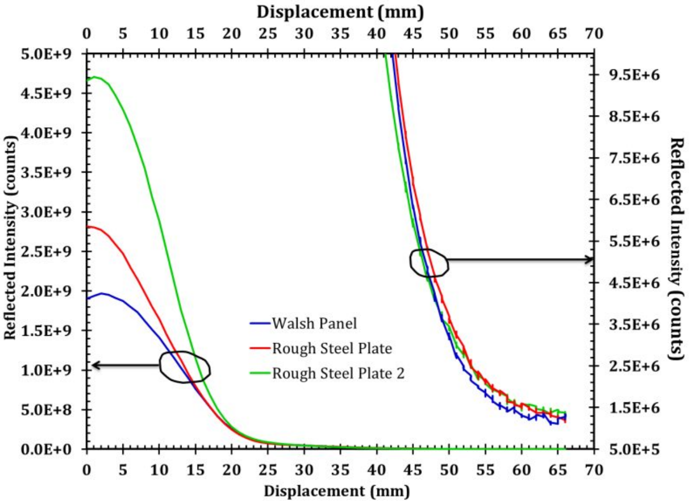

Fig. 3. Calibration of reflected intensity as a function of deformation (displacement).

Here the target, the terahertz source, and the detection system are organized such that the projectile path remains clear. With this orientation the source and the detection system was aligned such that the detector received the maximum power. A multilayered panel, mounted on a fixed platform, was then introduced in the beam path and the initial power was recorded. Then a cluster of a few layers of the panel was peeled off and transmission was measured again. This way transmitted power was recorded while other clusters from the panel were removed successively. For each cluster removed, a small disk was cut out (approximately equal to the beam spot) and its mass was measured on a micro balance. Fig. 5(a) shows the successive layers' mass dependence of the transmitted power. Fig. 5(b) shows the measured power vs. measured mass of the disks cut out of the peeled clusters. This will serve as the calibration for determining mass change during the ballistic impact. This calibration must be done á priori for a given geometry and for a given material.

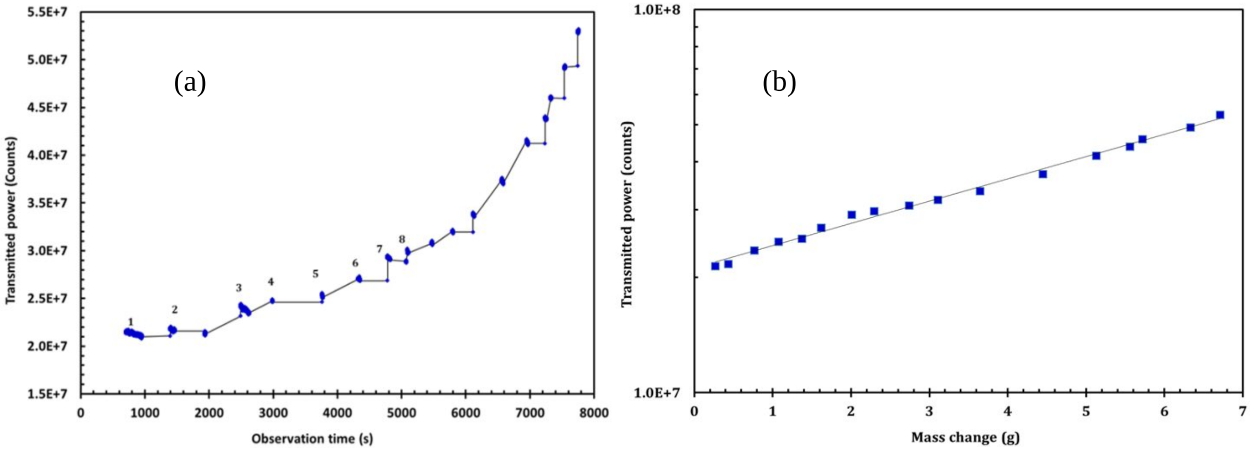

Fig. 5. (a) Transmitted power increases as successive layers are removed from the panel under calibration. (b) The transmitted power is plotted as a function of cumulative mass removed from the panel. The change in mass for this particular panel may be read from this curve or may be calculated from the fit: $Y = 2.11614423 \times 10^7 e^{0.13377147X}$, where Y is the transmitted power and X is the mass in gram. Note there are 8 digits after decimal for a better accuracy.

2. RESULTS AND DISCUSSION

Kinetics spectrum of a multilayered panel is shown in Fig. 6(a). Since the deformation calibration for this sample was not done ahead of time, the information available from a simultaneous digital image correlation (DIC) measurement [for a thorough review and discussion of DIC, see ref. 2] was used to calculate the deformation and propagation velocity profiles.

Fig. 8 shows a kinetics spectrum acquired in transmission utilizing the setup shown in Fig. 2(b). The change in transmitted intensity from t = 0 to the maximum inflection point may be used to compute the effective mass of the trauma generating volume from the calibration curve shown in Fig. 5 (b).

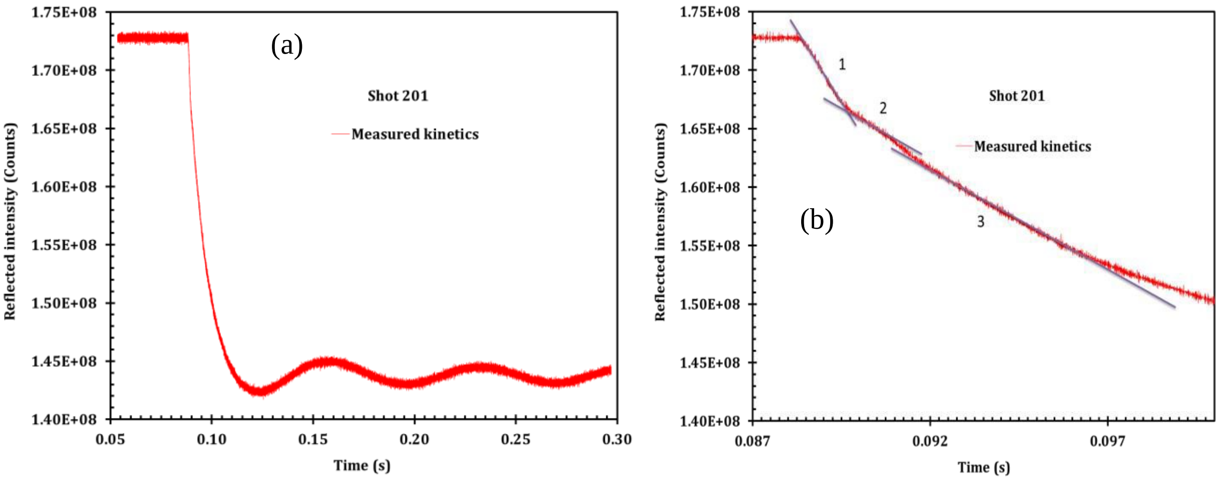

Fig. 6. (a) Kinetics spectrum of a live shot indicating the target underwent permanent deformation. The wavy nature at the tail end most likely occurred from the vibrations of the mounting platform. (b) Close-up of the kinetics spectrum. Although it seems to be a single slope from the strike point to the first inflection point, actually there are distinct slopes before the deformation reaches the maximum. This is indicative of delamination of layers in a cluster within the panel rather that every individual layer.

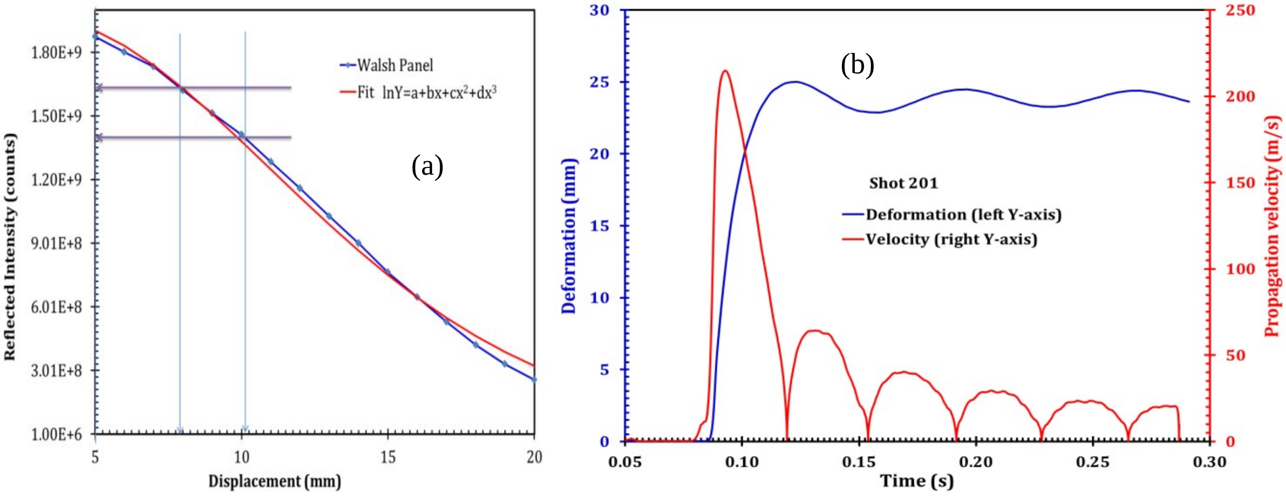

Fig. 7. (a) Deformation extraction from the calibration curve. (b) Deformation profile (left Y-axis) calculated from the kinetics spectrum of Fig. 6 (a) with a depth of 10.4 mm (from DIC under identical conditions). Calculated velocity profile of deformation is shown in the right Y-axis.

3. CONCLUSIONS

Terahertz kinetics spectroscopy under high speed data collection has been used to capture real-time kinetics spectra of ballistic events. Testing was done with prototype devices to demonstrate applicability for ballistic event characterization. Critical parameters such as deformation profile, maximum deformation and deformation propagation velocity profile were computed from the measured kinetics spectrum utilizing the non-relativistic equation of motion. The analysis for panels that are used for manufacturing Soldiers' helmets has been carried out for less-than-lethal ballistic impact i.e., the blunt criterion. Kinetics spectra from reflection measurements have been utilized for calculation of deformation profile and its propagation velocity profile. The kinetics spectra from transmission measurements can be used for calculating the mass change due to delamination or material evaporation in a ballistic impact. An example of mass calibration has been provided. This technique does not depend on the biomarkers; rather utilizes the impact energy measured in real time for trauma or concussion assessments. Thus, the technique may be used for diagnosing head injury under less than lethal cases. The same principle may be used for analyzing helmets used by athletes for detection of trauma, concussion or stigma.

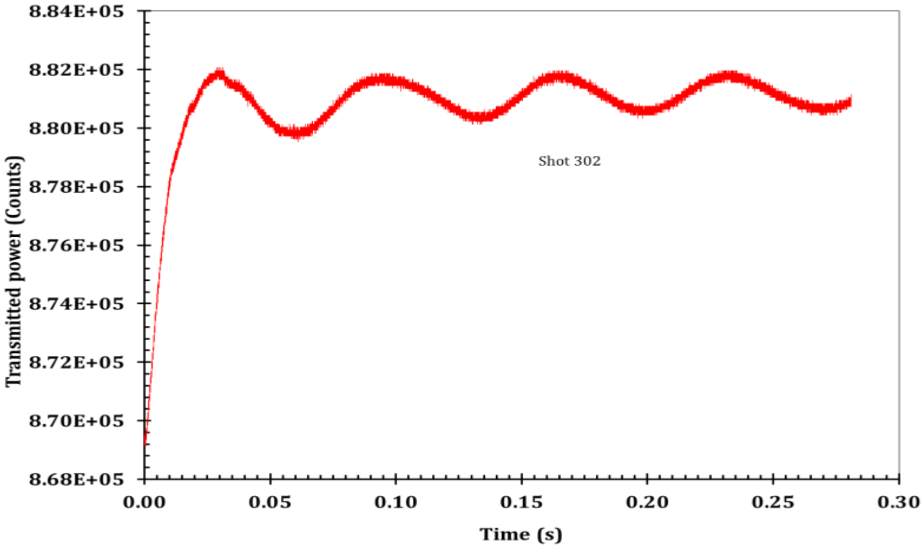

Fig. 8. An example of kinetics spectrum captured in transmission. The change in the transmitted intensity may be utilized to quantify the effective mass, m_{eff} from the calibration of the same material. This is used to quantify the energy E_{tr}.

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