Terahertz Dynamic Scanning Reflectometry of Soldier Personal Protective Material

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ABSTRACT

Ballistic characterization of improved materials for Soldier personal protective equipment is an ever-challenging task, requiring precise measurement of materials during ballistic impact. Current dynamic deformation technologies, such as high-speed digital image correlation, and laser velocimetry and vibrometry, are only able to provide surface measurements. However, there is a need to measure the dynamic delamination and mass loss of composite material, allowing calculation of available kinetic energy remaining in the material. A high sensitivity terahertz dynamic scanning reflectometer may be used to measure dynamic surface deformation and delamination characteristics in real-time. A number of crucial parameters can be extracted from the reflectance measurements such as dynamic deformation, propagation velocity, and final relaxation position. As proof of principle, an acrylic plate was struck with a blunt pendulum impactor and dynamic deformation was captured in real-time. Reflectance kinetics was converted to deformation and the velocity was calculated from the kinetics spectrum. Kinetics of a focused pendulum impactor on a steel plate was also acquired, characterizing plate relaxation from maximum deformation to equilibrium with discernible vibrations before reaching stable equilibrium.

Keywords: Terahertz Scanning Reflectometry, ballistic deformation, Soldier personal protective material, multi-layered material, deformation kinetics, real-time deformation relaxation

1. INTRODUCTION

Engineering of improved materials for Soldier personal protective equipment is an ever-challenging task involving characterization of relevant materials to help develop better helmet and body armor performance against ballistic and blunt impact threats. However, the current technologies are facing limitations in arriving at precise information regarding ballistic impact events that are crucial for effective characterization. A high sensitivity terahertz dynamic scanning reflectometer (TDSR) may be used to measure the dynamic surface deformation characteristics in real-time (in-situ) and also at post deformation (ex-situ). Real-time measurements can capture the kinetics of deformation of layered materials due to ballistic impact. Since terahertz radiation can penetrate many composite materials, it is expected to produce a clearer picture of the internal layers of composite laminates than is otherwise possible. A number of crucial parameters can be extracted from the kinetics measurement, such as the deformation length, the propagation velocity, and the final relaxation position, including any vibrational motions due to impact. In addition, for non-metallic substrates, a transmitted beam may be used to calibrate any mass loss of the laminate layers due to impact. This will allow computation of the force and energy of impact in real-time.

The current technologies have limitations in that they are not sensitive to certain important parameters, such as kinetics and dynamic mass loss that are crucial to fully quantify a ballistic event. Terahertz interaction with materials provides much higher sensitivity because the probing frequencies are sensitive to vibration of molecules as a whole as opposed to just a bond or its torsion. We successfully demonstrated application of the TDSR (Applied Research & Photonics (ARP), Harrisburg, PA) for capturing ballistic kinetics on an Army test-bed setting. Here a simulated ballistic experiment (see Fig. 1) was used for initial testing, while actual field tests are planned for the near future. ARP's TDSR received the 2011 CLEO/Laser Focus World's Innovation Award: http://www.cleoconference.org/media_center/conference_releases/2011/CLEO-Innovation-Award-Winner.aspx

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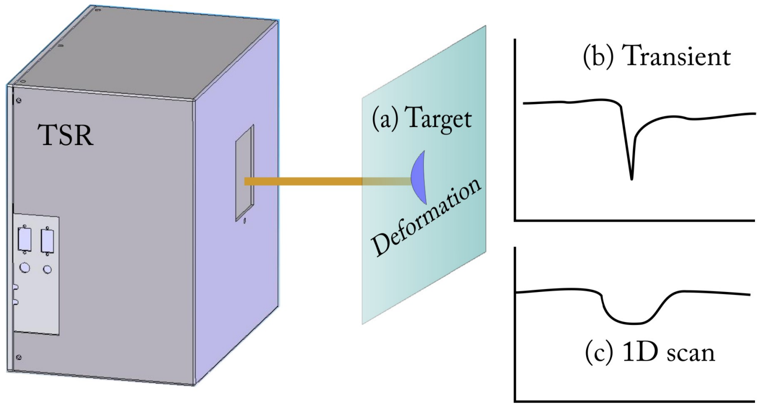

Fig. 1. A terahertz scanning reflectometer in horizontal orientation: (a) target, (b) sketch of the transient (kinetics) of deformation depth and recovery profile, and (c) is a sketch of 1D scan across the deformation.

ARP's current TDSR design is based on normal incidence of the terahertz beam to the target. In case of normal incidence, the incident beam is the sum of the reflected, transmitted and absorbed intensities. Assuming the material properties remain unchanged during the impact, real-time measurement of reflectance represents the deformation at the point of impact. 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 becoming a function of time, $l(t)$, due to deformation. Since the reflectance, R, is proportional to the variation in path length, measurement of $R(t)$ can yield the dynamics of deformation.

As illustrated in Fig. 1, when the terahertz beam reflected by the target (see 1(a)), the transient due to impact (1(b)) represents the nature of deformation at impact. However, a difficulty with the normal incidence configuration is that it is not the most suitable configuration for field testing of actual ballistic events; because, in case the projectile penetrates the target, it may damage the machine via direct impact in its path. Therefore, an important goal is to design a machine such that the transmitter and the detection unit may be mounted separately in an angular orientation such that the vulnerabilities for direct hit with a projectile may be avoided. This configuration is illustrated in Fig. 2.

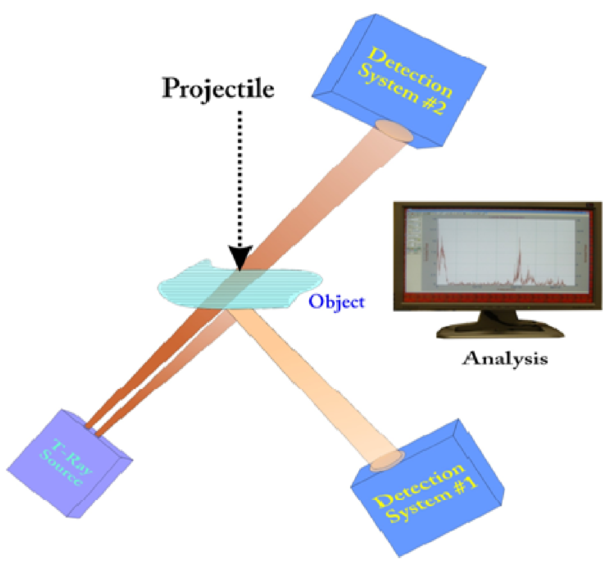

Fig. 2. Concept configuration of a two-channel terahertz dynamic scanning reflectometer (TDSR) for real-time kinetics of ballistic events.

1.1. Kinetics

The TDSR uses a continuous wave (CW) terahertz source that generates broadband terahertz radiation from an electro-optic dendrimer [1]. The terahertz beam is focused on the specimen at normal incidence while a matching detection system captures the reflected beam at a suitable distance (see Fig. 3). At this configuration a sudden impact results in a transient that is directly related to the deformation characteristics. The following parameters can be extracted from the kinetics spectra:

a. Maximum deformation (l_{max})
b. Time to maximum deformation (Δt)
c. Position of the final relaxed state (l_τ)
d. Relaxation time (τ)
e. Deformation speed (V_{max}).

These parameters will be used to uniquely characterize different candidate materials as well.

1.2. Delamination

Another crucial factor in the characterization scheme is the delamination of interior layers of a multilayered material. An important feature of terahertz radiation is the ability to penetrate many materials, including multilayer nonmetallic helmets and body armors. This facilitates inspection of delamination, inclusions, and impregnation by foreign particles. Additionally, the calibrated transmitted beam provides the change in mass at impact from which the impact force may be computed by combining with kinetics data.

2. Experimental

Deformation kinetics of a Plexiglas™ plate and a steel plate were measured using the setup shown in Fig. 3. A Plexiglas plate was mounted on a mandible, struck with a pendulum and the ballistic kinetics was captured in real-time (Fig. 4). Fig. 5 shows the computed deformation where the reflectance kinetics was converted to a known deformation of 27 mm (from digital image correlation [2]) and the propagation speed calculated from the kinetics spectrum.

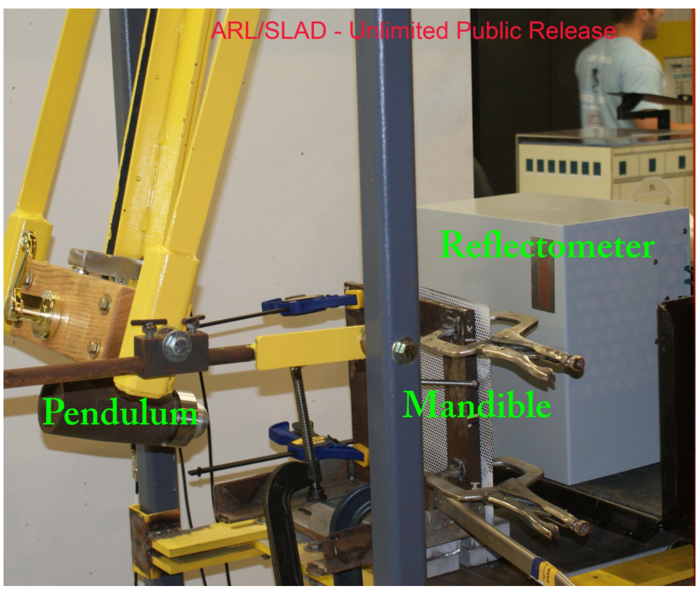

Fig. 3. Picture of the experimental setup.

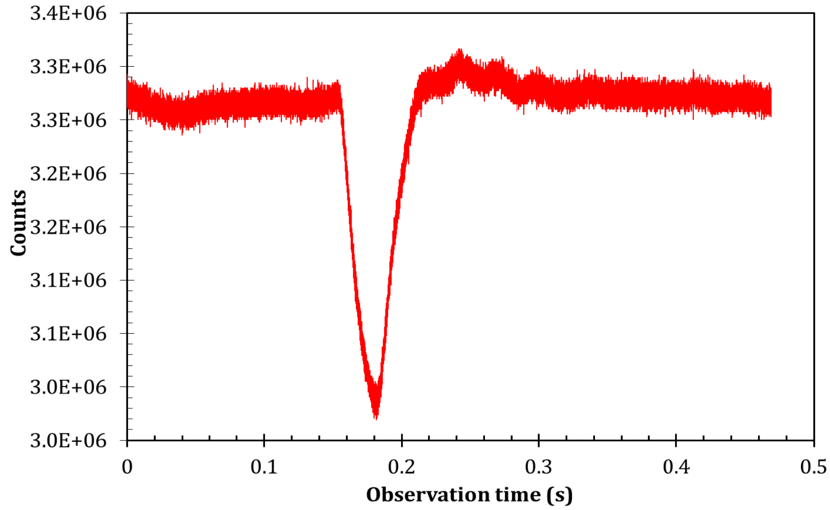

Fig. 4. Deformation kinetics of a Plexiglas plate mounted on the mandible and struck by the pendulum with wide head.

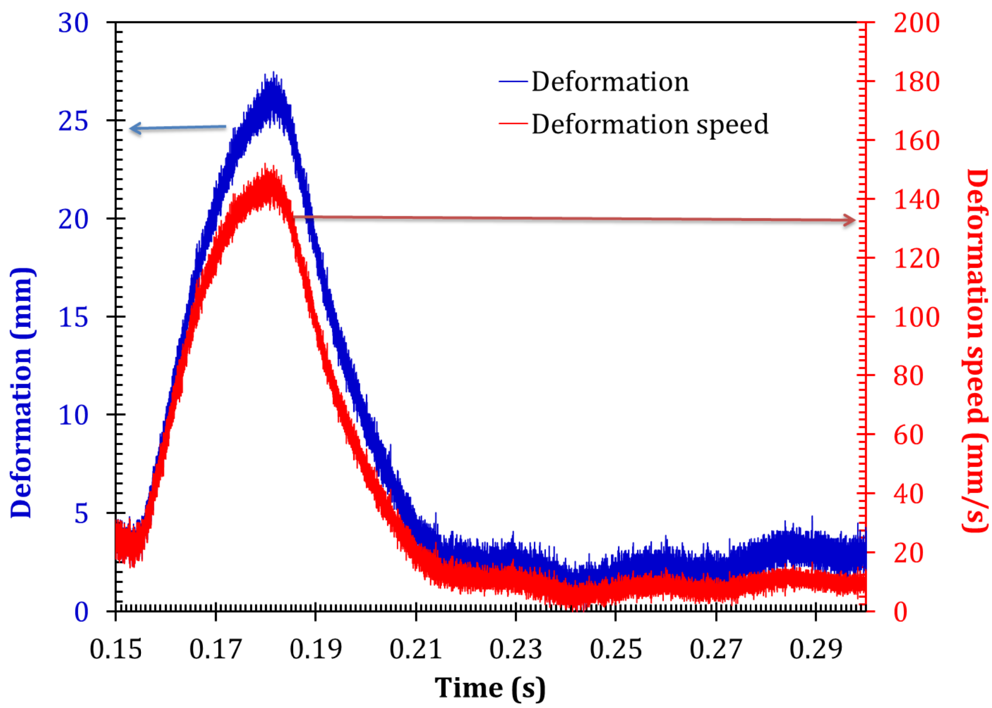

Fig. 5. Plexiglas deformation calculated from the kinetics data of Fig. 3 (blue curve) 27 mm (from DIC) over ~30 ms. Propagation speed of deformation is shown in red.

A close-up of Fig. 5 is shown in Fig. 6, indicating that the deformation propagation speed lags the deformation by about 2.5 ms. Fig. 7 shows the kinetics of a pointed pendulum drop on a steel plate mounted on the mandible. The plate relaxed back from maximum deformation to a position of equilibrium with visible vibrations before reaching stable equilibrium. Fig. 8 shows the calculated deformation (assumed 10.6 mm) and its speed of propagation.

3. Results and Discussion

The data presented in the above section demonstrate the capabilities of terahertz reflectometry in capturing real-time kinetics of the ballistic events. The calculated parameters for the two samples are given in Table 1.

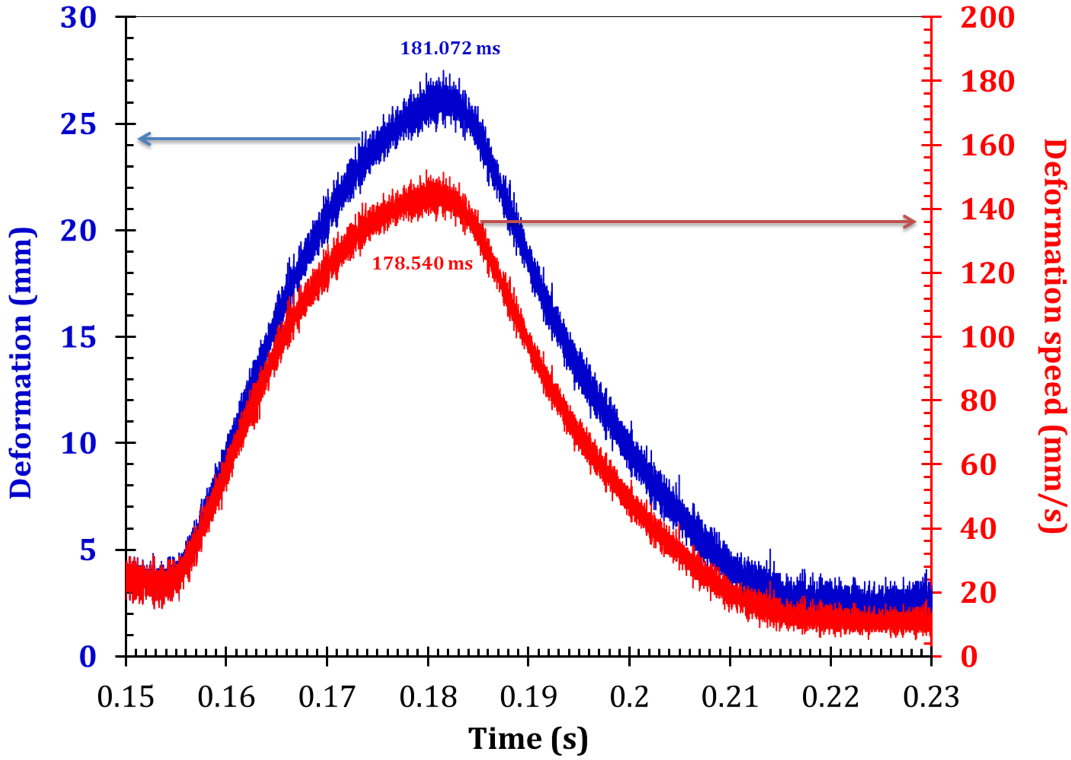

Fig. 6. Close-up of Plexiglas deformation (Fig. 5). Maximum deformation speed precedes maximum deformation by ~2.532 ms.

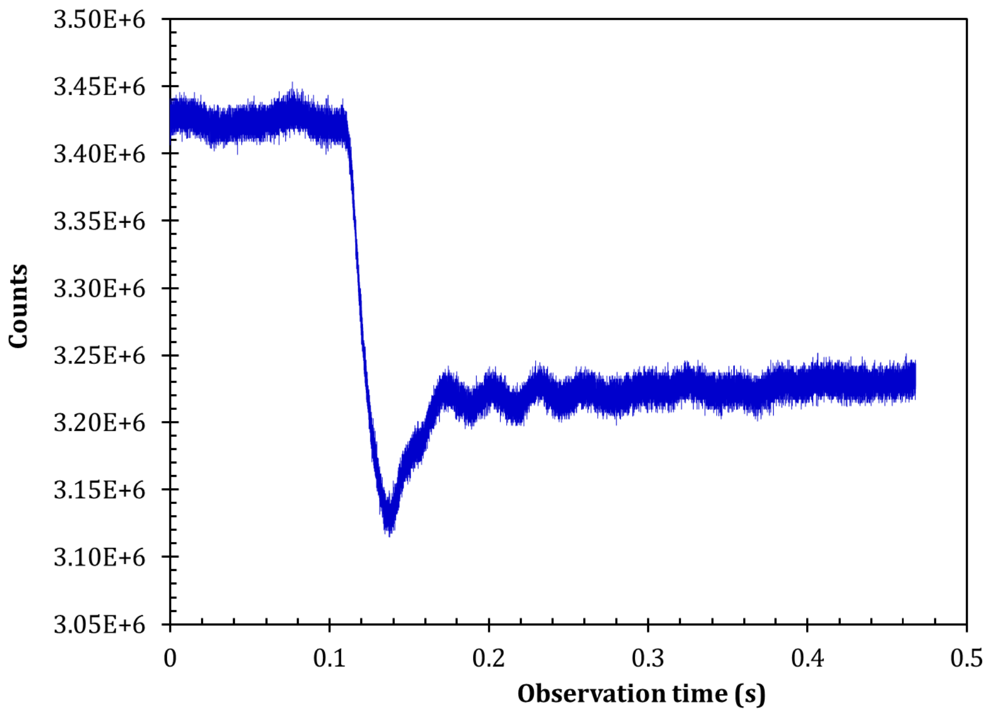

Fig. 7. Ballistic kinetics of a steel plate mounted on mandible.

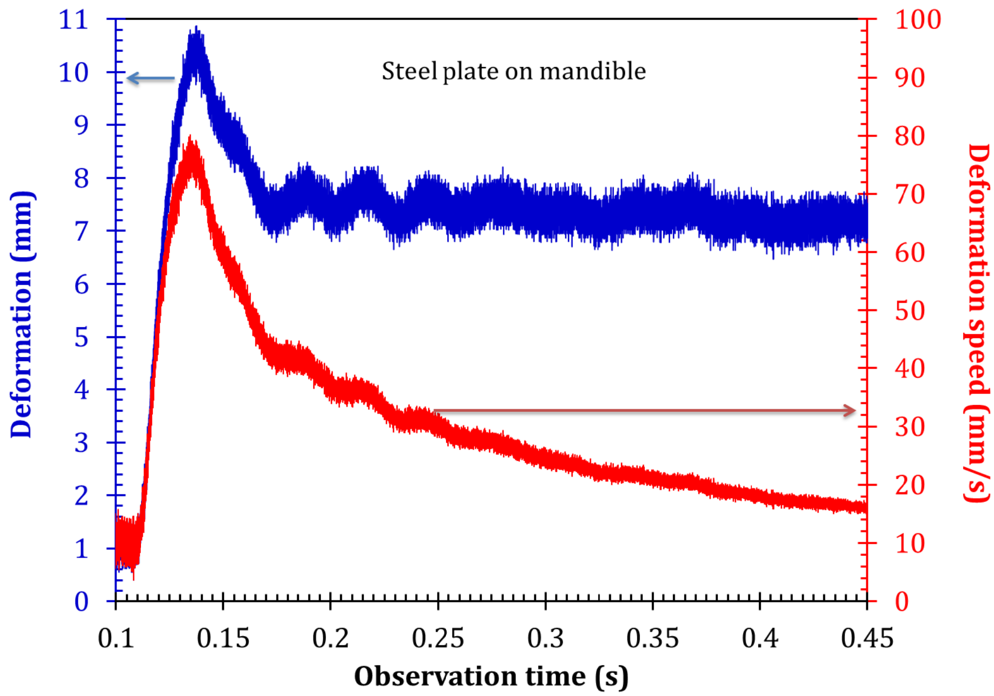

Fig. 8. Deformation of a steel plate with relaxation. The pendulum with a pointed head was dropped from 13" height.

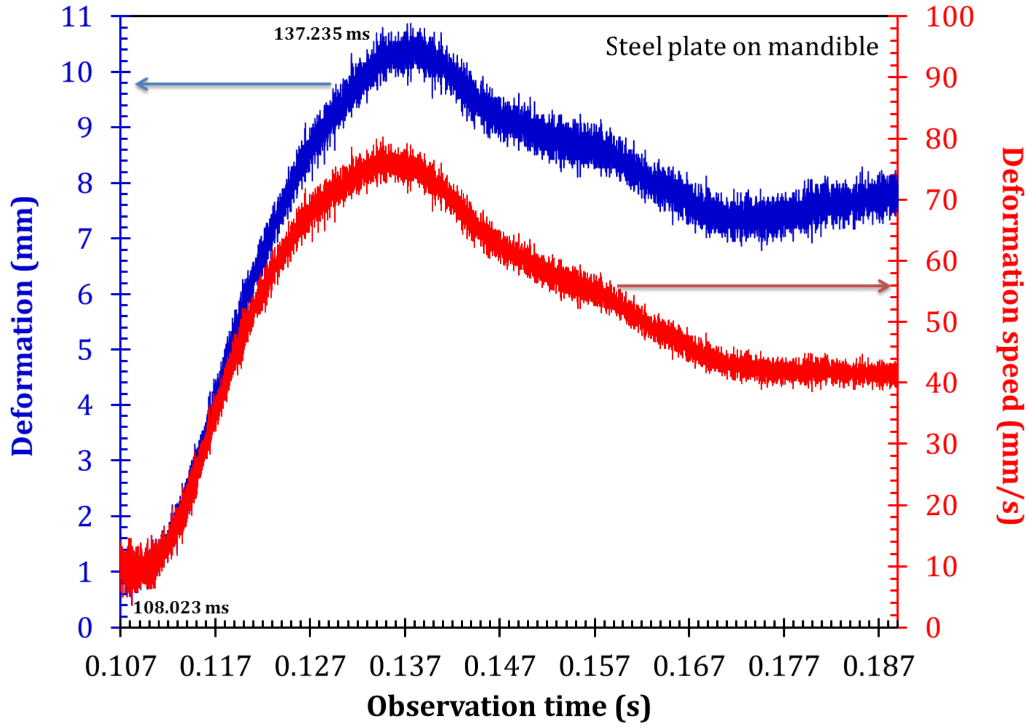

Fig. 9. Close-up of Fig. 8. Deformation peak time is ~29.212 ms. The speed profile is calculated assuming maximum deformation ~10.6 mm.

Table 1. Calculated parameters for the two samples

Sample \ Parameter	l_{max} (mm)	Δt (ms)	l_τ (mm)	τ (ms)	V_{max} (mm/s)
Plexiglass	27	30	~0	~38	~145
Steel plate	10.6	29	~7.5	~35	~80

In case of a Soldier's helmet, an important quantity is the available energy for potential impact to the head. At the point of impact, this is simply the kinetic energy of the projectile:

$$E_k = \frac{1}{2} m_p V_p^2, \qquad (1)$$

where E_k is the kinetic energy, m_p is the mass of the projectile, and V_p is the impact velocity of the projectile. It has been indicated by Sturdivan [3] that the physical quantity that properly expresses the capacity to do work on tissue and cause damage from blunt impact is, "energy." He expressed the blunt criterion (BC) as a measure to predict head injury from blunt, less-than-lethal projectiles, as

$$BC = ln\left(\frac{E}{T*D}\right), \qquad (2)$$

where E is the impact kinetic energy in Joules, D is the diameter of the projectile in centimeters, and T is the thickness of the skull in millimeters. However, one needs to recognize that, as a projectile (e.g., a bullet) hits the outside of a helmet, the impact causes the inside of the helmet to deform (bulge) inwards, thus imparting energy on a Soldier's head. It is this energy – that is significantly less than the impact kinetic energy of the projectile on the helmet's exterior – that causes injury. Thus we recognize that the deformation propagation velocity is the main quantity; the kinetics data (e.g., Fig. 5) gives this velocity profile accurately.

4. Summary

In conclusion, a terahertz dynamic scanning reflectometer may be used to capture real-time kinetics of ballistic events. Proof of concept testing was done on prototypes to demonstrate the applicability of the TDSR in real ballistic event characterization. Detailed testing on helmet and other candidate materials will be conducted to work out the details for a field test unit.

5. References

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