Simultaneous Shock and Particle Velocities Measurement using a Single Microwave Interferometer on Pressed TATB Composition T2 Submitted to Plate Impact

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Abstract. Microwave interferometry has been applied to study the shock initiation response of TATB-based HE samples in order to perform the simultaneous measurement of the shock and particle velocities. The particle velocity characterization is not possible with the standard phase method. Therefore the new analytic electromagnetic wave propagation method, based on the Doppler frequency shifts of reflecting moving dielectric interfaces, has been developed and applied to the single sustained shock experiment. The experimental results are compared with hydrocode numerical simulations and a good agreement is observed.

Introduction

Wedge test, single and double shock experiments are usually performed to implement or qualify SDT (Shock to Detonation Transition) reactive flow modeling of high explosives (HE) with chronometric pins, streak camera, Manganin pressure or particle velocity gauges. Carrying out simultaneous measurements is challenging, because different physical principles are involved: piezoresistivity, piezo-electricity, magnetism or photoelectricity.

The ElectroMagnetic Velocity (EMV) gauges are intrusive, but convenient for measuring the shock and particle velocities with 9 aluminum wires (0.5-mm spatial resolution) and 3 shock trackers (0.2-mm spatial resolution) placed inside the sample under an external magnetic field[1]. The non-intrusive Photonic Doppler Velocimetry method has been developed for transparent materials[2]. Multiple Manganin gauges are applied for shock and pressure measurements and a 5-mm spatial resolution has been achieved[3]. Microwave interferometry was applied over the years[4] and requires the knowledge of pristine relative permittivity to determine the shock velocity, and is limited by the lack of shocked relative permittivity data for the particle velocity analysis.

A new analytic electromagnetic wave propagation method has been proposed for steady shocks[5] and relies on the Doppler frequency shifts generated by reflecting moving dielectric interfaces and on the relative amplitudes of the reflected signal. A set of equations links the shock velocity, particle velocity and the shocked relative permittivity to some key signal descriptors.

A review of the pristine relative permittivity determination methods with the associated measurement uncertainties was also reported recently[6]. Therefore, a new tool for complex permittivity measurement has been developed based on the transmission method between 70 and 110 GHz.

In this paper, we apply the new analytic electromagnetic wave propagation method and the pristine relative permittivity determination technique to study the shock behavior of TATB-based composition T2 subjected to single impact experiments.

Experimental configurations and raw signals

Shock initiation experiments are performed with the single stage gas gun DEIMOS or the powder gun ARES with impact velocities ranging from 770 to 1035 m/s. The table 1 and figure 1 present the shock experimental conditions. The inert input pressure in the HE sample has been calculated with hydrodynamic assumption based on the material Hugoniot value. The CuC_2 copper flyer is 85 mm in diameter and 15-mm thick. The copper buffer plate is 4-mm thick and the composition T2 HE sample is 85 mm in diameter and 30-mm thick. Two Manganin gauges are placed within the HE, 10 mm from the buffer plate. Microwave (MW) and laser interferometry are also applied at the back of the sample. The MW signals are analyzed in this paper.

The figures 2 to 5 present the raw signal of the copper plate impact at different impact velocities on the T2 composition. Two frequencies are typically obtained: the high one is related to the moving shock interface inside the sample while the low one is associated with the transfer plate interface. The attenuation of the low frequency signal is very fast during the first period for the two highest impact velocities experiments. Three (and sometimes four) periods are measured for the two lowest impact velocities experiments. The amplitude of the high frequency signal generally increases with time toward the back of the HE sample and is associated with smaller signal losses.

Table 1. Shock experimental conditions

Shots	**Vi(m/s)**	**Tilt (mrad)**	**Inert P calc.(GPa)**
1	1034.5±13	2.5	6.67±0.12
2	847.9±25.9	3	5.06±0.21
3	798.7±14.7	2.8	4.67±0.12
4	770±17	3	4.44±0.12

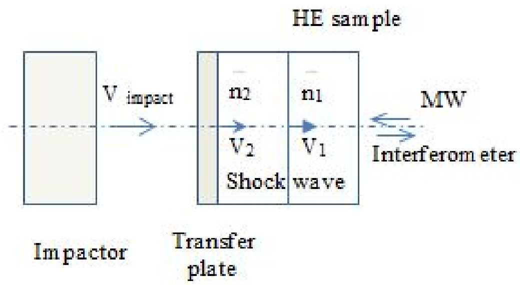

Fig. 1. Sketch of the experimental set-up.

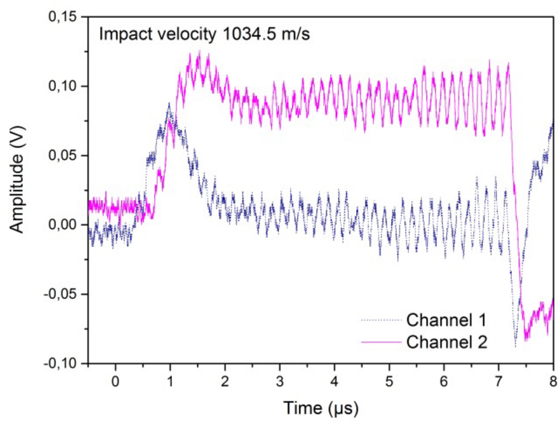

Fig. 2. Raw microwave signals for the single shock and impact velocity of 1034.5 m/s.

Numerical codes

Numerical hydrocode simulations are performed with the reactive flow model Ameto[7] to compare with the experimental results using the new analytical EM method.

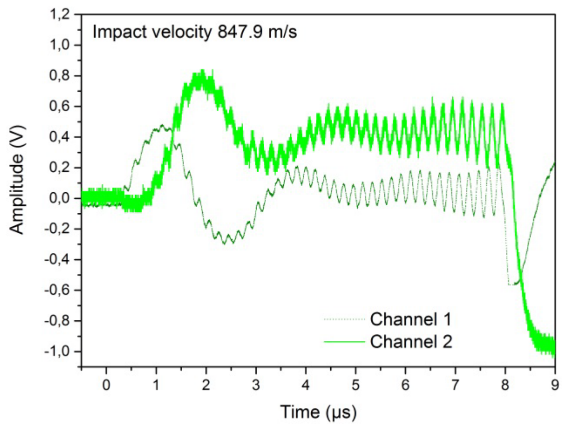

Fig. 3. Raw microwave signals for the single shock and impact velocity of 847.9 m/s.

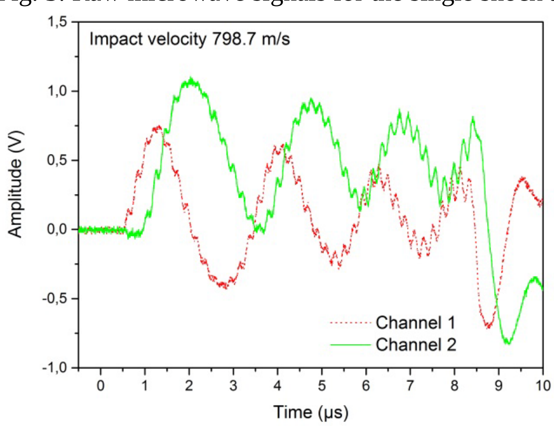

Fig. 4. Raw microwave signals for the single shock and impact velocity of 798.7 m/s.

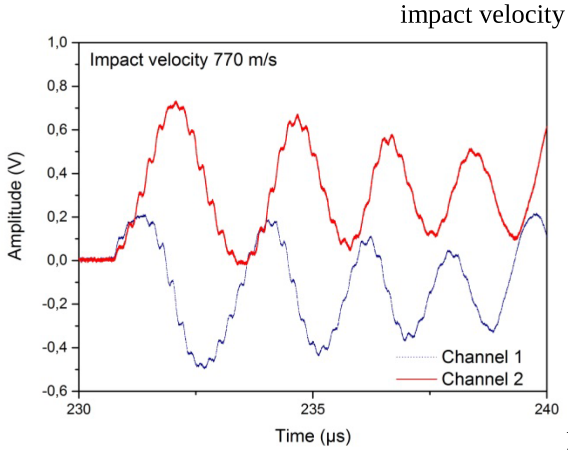

Fig. 5. Raw microwave signals for the single shock and impact velocity of 770.0 m/s.

The analytic electromagnetic wave propagation method has been applied to two layers moving at different velocities associated with the steady shock propagating through the HE sample and the motion of the transfer plate interface. The set of equations (1) relies on the Doppler frequency shifts and reflected electromagnetic field amplitudes associated to each of the reflecting interfaces, *i.e.* the shock front and the interface between the shocked material and the transfer plate.

The equations are then derived and link the velocities and the relative permittivity of the shocked material to the measurable signal parameters[5]:

$$V_1 = \frac{c}{2n_1} \times \frac{f_1}{f_c}$$

$$V_2 = V_1 + \frac{c}{2n_2} \times \frac{f_1 - f_2}{f_c} \qquad (1)$$

$$R_a n_1^2 + 4n_1 n_2 \left(1 + \frac{f_1 - f_2}{f_c}\right) - R_a n_2^2 = 0$$

where V_1 and V_2 are respectively the shock wave velocity and the particle velocity, c is the velocity of light in vacuum, n_1 and n_2 are respectively the refractive index of the unshocked and shocked material respectively, f_1 and f_2 are the Doppler frequency shifts associated respectively to the reflection on the shock front and on the transfer plate respectively, fc is the operating frequency of the MW interferometer and R_a is the ratio of the amplitude associated to the transfer plate interface and the amplitude associated to the shock front.

The identification of the frequencies is first performed using a FFT algorithm, and improved with a Levenberg Maquardt least square method based on a sinusoidal preform function. Table 2 presents the measurable parameters obtained from the MW interferometer raw signals for the four single shock experiments. The uncertainty on the value R_a is quite high for the shot n°1 due to the very low amplitude of the reflected signal associated with the chosen MW interferometer signal amplifier parameters.

Table 2. Parameters derived from the electromagnetic wave propagation method and the MW interferometry approach

Shots	**f_1 (MHz)**	**f_2 (kHz)**	**Ra**
1	5.43±0.08	278.2±9.4	17.2±6.8
2	5.32±0.08	307.6±9.4	16±1.1
3	5.06±0.08	335.2±9.4	16.3±1.2
4	5.06±0.03	362.5±2.5	16.8±1.6

The dielectric constant of the TATB-based HE sample has been obtained from two methods: (1) a static approach based on S-parameters matrix recording with a new static transmission system and (2) a dynamic approach based on the detonation front tracking method (this method compares the MW interferometer detonation front velocity at the back of a bare cylinder charge to the lateral piezopins one). For this second method, the MW interferometer records are analyzed with two techniques: a phase one (corresponding to a Lissajous method) and a Doppler frequency one. The discrepancy between the two front tracking techniques is low, typically under 1.4 %. The difference between the static and the dynamic methods is under 1.0 %. The static relative permittivity is 4.42±0.06 and is used in this paper. The loss properties have also been identified but not applied yet in the electromagnetic wave propagation method.

Experiment-calculation comparisons

Table 3 lists the shock, particle velocities and shocked refractive index computed from the electromagnetic wave propagation method for the four shock experiments. The figure 6 presents the shock and particle velocity comparisons between the experimental results and the data obtained from hydrocode numerical simulations. The experimental shock velocity values have been obtained with the phase method from the complete MW interferometer records. The experimental particle velocity has been derived from the electromagnetic wave propagation method. For this last method, the frequencies have been analyzed only on the first microseconds of the signals.

The comparison between the phase method and the reactive hydrocode numerical simulations for the shock front is under 2.0 % between 3.5 and 5.5 µs before the side release wave arrival, as one can see in figure 6. It can be noticed that the velocity decreases after 6 µs due to the side position of the antenna at the back of the sample. The particle velocity cannot be extracted from the phase method. The electromagnetic wave propagation method has been developed for such measurements. The difference between the electromagnetic wave propagation method and the hydrocode numerical simulations for the shock velocity is slightly higher up to 4.0 %, due to the identification of the high frequency during the first period of the raw signal. The discrepancies for the particle velocities are respectively 5.3, 3.0, 0.6 and 3.7 % for the shots n°1 to 4.

These results could be correlated with the reaction rate observed with Manganin pressure gauges within the HE.

Table 3. Shock, particle velocities and shocked refractive index estimated from the electromagnetic wave propagation method

Shots	V_1 (m/s)	V_2 (m/s)	ε_{r2}
1	4169±135	802±159	5.98±0.1
2	4038±130	679±60	5.67±0.04
3	3840±128	667.6±59	5.65±0.04
4	3837±51	673±71	5.60±0.05

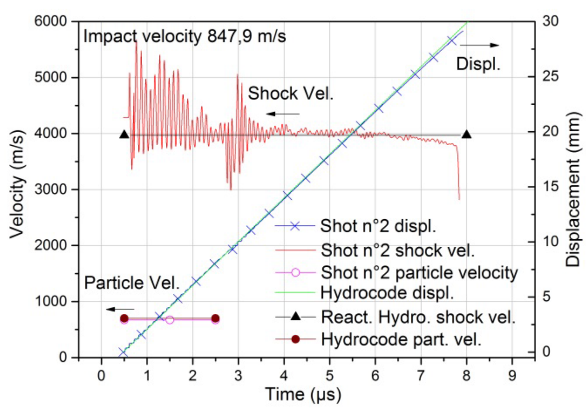

Fig. 6. Displacement, shock and particle velocity comparisons between experimental and simulation results for an impact velocity of 847.9 m/s.

The less reaction growth is characterized on the pressure signal slope, the less discrepancy is found on the determination of the particle velocity. Therefore, one should expect the shot n°4 to have the best agreement as the pressure is near the reactive threshold. However, the input parameters for the electromagnetic model are obtained with a computed Pearson coefficient around 0.94 for the shot n°4, when the others show a typical Pearson coefficient around 0.98.

Conclusions

The shock initiation threshold of the TATB-based composition T2 subjected to a single sustained impact has been studied with a MW interferometer through the radio-transparent HE sample. The two frequencies of the reflected MW signal is characterized and analyzed from a new analytic electromagnetic wave propagation method based on the Doppler frequency shifts of the reflecting moving interfaces and on the relative signal amplitudes. The shock and particle velocities and the shocked relative permittivity have been estimated from the pristine relative permittivity and the MW signal parameters. The high-frequency low-amplitude signal has been associated with the moving shock wave, while the low-frequency high-amplitude has been associated with the HE/transfer plate interface.

The comparison with hydrocode simulation results gives a good agreement. To reach better accuracy, the key parameter is the identification of the high and low frequencies and amplitudes, which could be improved with machine learning algorithm.

References

[1]. Sheffield S., Gustavsen R., Alcon R., AIP Conf. Proc., Shock Compression of Condensed Matter pp.1043-1048 (1999)

[2]. Armstrong M., Crowhurst J., Bastea S., Zaug J., Journal of Applied Physics 108, 4023511 1-9 (2010)

[3]. Vandersall K., Tarver C., Garcia F., Steven K. Chidester S., Urtiew P., Forbes J., Int. Det. Symp. (2006)

[4]. Cawsey, G., Farrands, J., Thomas, S., Proceedings of the Royal Society of London, 499-525 (1958)

[5]. Rougier B., Aubert H., Lefrançois A., Barbarin Y., Luc J., Osmont A., "Reflection of Electromagnetic Waves on Moving Dielectric Interfaces for Analyzing Shock Phenomenon in Solids," RadioScience, 2018.

6. Rougier B., Lefrançois A., Chuzeville V., Poeuf S., Aubert H., "High Explosives Static and Dynamic Relative Permittivity Measurements in the W Band To Investigate Shock and Detonation Phenomena," Propellants, Explosive, Pyrotechnics, under revision, 6 June 2018

7 Bouton, E., et al., "Development of a Reactive Burn Model based upon an Explicit Visco-Plastic Pore Collapse Model", AIP Conf. Proc., 2015

Question from Allen Kuhl
There can be diffusion at discontinuities, would that affect the rise profile of your MW signal?
Answer from Benoit Rougier
The HF antenna integration has been calculated with the CST code (Computer Simulation Technology) and shows a collimated emission and reception through the interfaces.

Question from Sam Emery
If the absorption losses could be quantified, could the reaction zone chemistry behind the detonation front be characterized in a meaningful way?
Answer from Benoit Rougier
The absorption losses have been measured only for the pristine sample. The amplitude of the low frequency is decreasing as fast as the reaction growth. The issue is to characterize dielectric properties of the reaction zone. Nevertheless, the radiofrequency could be very accurate to detect very little change in permittivity. The first step consists in determining if the ionization occuring in the reaction zone allows the sensing of this zone. If the detonation front is highly ionized, the incoming radiation cannot be transmitted through the front.