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Time-Resolved Temperatures of Shocked and Detonating Energetic Materials

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TIME-RESOLVED TEMPERATURES OF SHOCKED AND DETONATING ENERGETIC MATERIALS

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Chemical processes occurring in shock-compressed and detonating high explosives have been studied using fast time-resolved emission spectroscopy and a two-stage gas-gun. The spectral characteristics of emission from shock-compressed nitromethane, tetranitromethane and single crystals of pentaerythritol tetranitrate are typically very broad and structureless, likely representing thermal emission. Assuming the thermal emission from a gray-body, the emission intensity can be correlated to the temperature changes in shock-compressed and detonating high explosives. We report Chapman-Jouguet temperatures of 3800 K for nitromethane, 2950 K for tetranitromethane, and 4100 K for pentaerythritol tetranitrate. In this paper we also compare the data with the chemical equilibrium models.

INTRODUCTION

The shock temperatures of high explosives (HE's) are important for understanding shock-initiation and detonation processes; however, it has been one of less understood thermodynamic variables. On the other hand, unlike other variables like pressure or energy, the temperature is very sensitive to chemical equilibrium models which require experimental verification. In our previous study[1] we demonstrated a method to measure the time-resolved thermal emission from shocked and detonating nitromethane (NM). In this paper, we explain how the time-resolved thermal emission data can be correlated to the temperatures at various thermodynamic states such as the Chapman-Jouguet (*CJ*) condition. We will also present the results of other homogeneous high explosives like tetranitromethane (TNM) and pentaerythritol tetranitrate (PETN) single crystals.[2] The homogeneous high explosives are used to simplify the problem by separating other complicated mechanical issues associated with hot spots, non-ideal density, grain boundaries, etc.

EXPERIMENTS

Figure 1 shows the experimental setup for time-resolved temperature measurements of shock-compressed and detonating high explosives. HE sample is loaded in the 6 to 8

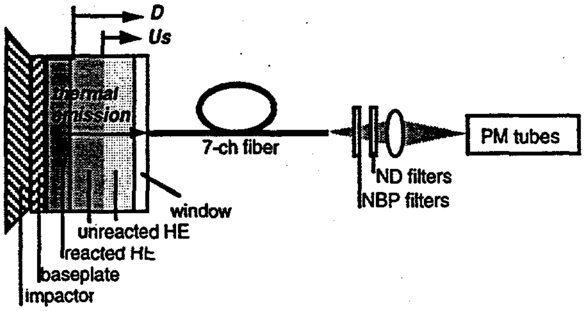

FIGURE 1. The experimental setup for time-resolved shock temperature measurements of transparent homogeneous high explosives.

UH

mm cavity between a baseplate and a transparent window and is shock-compressed by using a two-stage gas-gun which can accelerate an impactor up to 8 km/s.

The thermal emission from shock-compressed high explosives is time-resolved by using six photomultiplier tubes in the spectral range between 350 and 700 nm.[3] In this setup, thermal emission is collected from the central 3 mm area of HE, limited by the acceptance cone of an optical fiber bundle. This results in fast time resolution, a few ns, primarily depending on the rise time of recording electronics. The temperature of HE is then obtained by fitting this time-resolved thermal emission data to a gray body Plank function at 1 ns intervals during the event of interest, typically 1 μs.

SHOCK-INITIATION AND DETONATION

In homogeneous HE's the chemical reaction is believed to initiate behind the shock front near the baseplate/HE interface as shown in Fig 1.[4-7] This means that the detonation initially occurs initially from the shock-compressed HE (superdetonation), but later from the unshocked HE (detonation) as the detonation front catches the shock front. Figure 2 illustrates the thermodynamic states through which homogeneous HE molecules are evolved under shock compression.

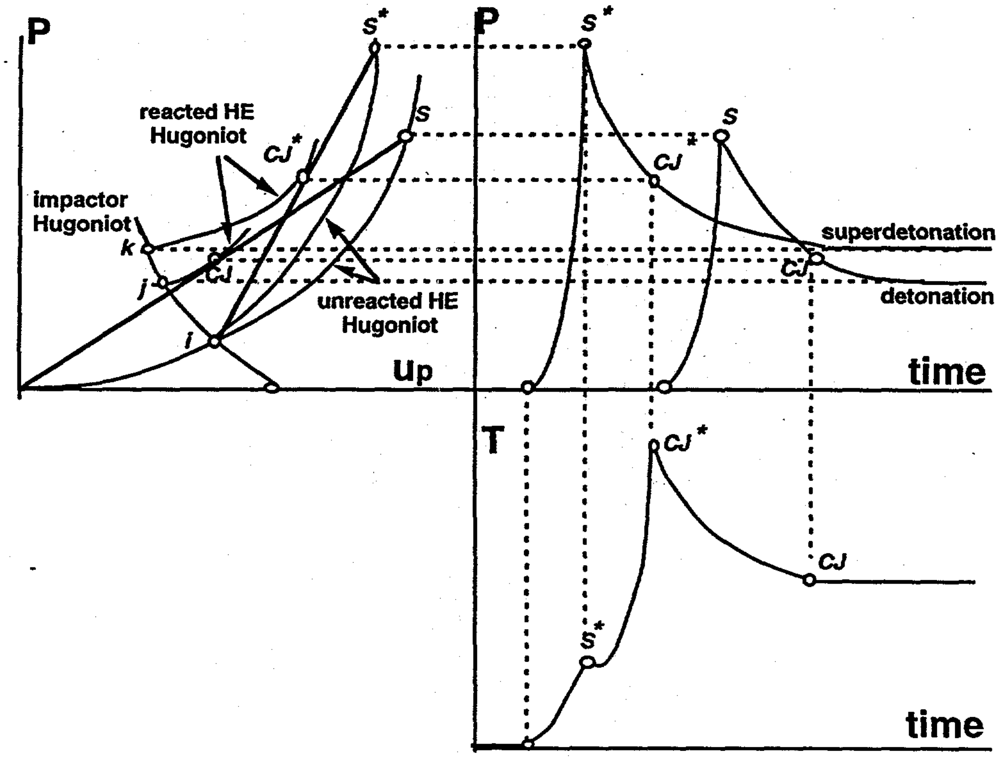

FIGURE 2. The thermodynamic states of shock-compressed and detonating homogeneous HE and the reaction products, together with the pressure and temperature changes at the reaction front.

The initial shock condition, *i*, is defined by the impedance match between an impactor and unreacted HE. The pressure of this shocked but unreacted HE increases to the von-Neumann spike, S^*, by chemical energy behind the shock front. The chemical reaction then initiate at S^*, and the products eventually evolve to the CJ^* state as the reaction is fully developed. These detonation products are then expanded isentropically to the condition matching the impedance of the impactor *k*, as long as the reaction front remains behind the shock front. In the later time, however, the detonation front catches the shock front, and the detonation occurs directly from unshocked HE at *S*, and the products evolve to the *CJ* and to the impedance match condition, *j*, between the isentropically expanded HE products and the impactor.

The temperature, on the other hand, increases as the reaction progresses and peaks at the *CJ*. The opacity of the reaction products is substantially higher than that of unreacted HE, due to formation of graphite and other hydrocarbons at high temperatures. Under these conditions the thermal emission measured across the reaction zone (Fig 1) is mostly from the reaction front and can be correlated to the temperatures at various thermodynamic states discussed in Fig 2. For example, the measured temperature will initially increase to that at S^* prior to shock-initiation and to the CJ^* temperature of shock compressed HE products. Then, the CJ^* temperature decays to the *CJ* temperature, as the detonation front catches the shock front. The measured temperature should then remain at the *CJ*, as long as the impact condition is same or below the *CJ* condition.

TIME-RESOLVED TEMPERATURE

Figure 3 shows the time-resolved temperatures of NM, TNM, and (110) PETN single crystal shocked to 10.7, 12.9 and 13.3 GPa, respectively. The temporal profiles are similar to one discussed in Fig 2 and can be characterized into the pre-detonation, superdetonation and normal detonation zones. The shock-initiation is evident from the initial increase in temperature and the subsequent small decrease in the pre-detonation zone. The induction times of the reactions are: 50 ns in NM and PETN and 200 ns in TNM. The second strong temperature jump indicates the detonation of these shock-compressed and reacting high explosives. The transitions to the CJ* states occur in 20-50 ns in TNM and PETN but in 200 ns in NM. The peak temperatures then decay to steady-state values for the next 100-400 ns, representing the transition to the detonation of uncompressed HE. Notice that, unlike TNM and NM, PETN detonates at substantially lower pressures than the *CJ* pressure near 31 GPa, consistent with the previous observation that PETN is sensitive along the (110) direction.[8]

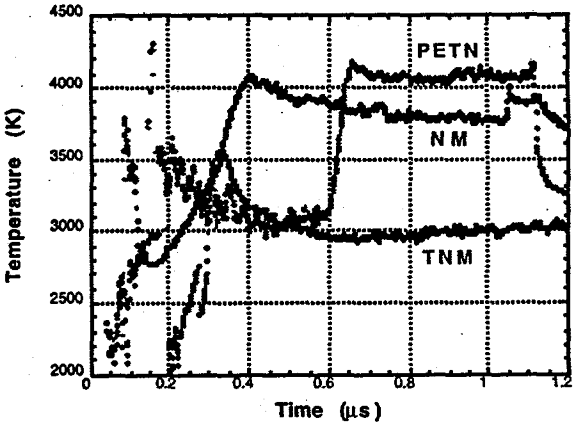

FIGURE 3. Time-resolved shock temperatures of selected homogeneous HE's.

The *CJ* temperatures of these explosives can be obtained from the steady-state values shown in Fig 3. The results are summarized in Table I, together with the calculated *CJ* temperatures using a chemical equilibrium code for comparison.[9] The *CJ* temperature of PETN is higher than other two due to the abundance of oxygen. The *CJ* temperature TNM is substantially lower than that of NM, likely due to the absence of hydrogen in TNM.

TABLE I. The steady-state temperatures of shock compressed homogeneous high explosives in comparison with the calculated *CJ* temperatures.

HE	P (GPa)		T (K)	
	unreacted	reacted	Steady-state	CJ_{cal}
NM	107	128	3800	3750
TNM*1	129	137	2950	2640
PETN	133	191	4100	4430

*1 98 % pure TNM was used in experiments and the calculation was also done based on 98 % TNM mixed with 2 % NM.

In summary, we have presented the time-resolved temperatures of shock compressed homogeneous high explosives including NM, TNM and PETN single crystals. The time dependence of temperature is crucial to understand how and when the HE molecules evolve to a steady state condition and, thus, to accurately determine the *CJ* temperature. It also reveals the pre-detonation behavior of HE's that can be correlated to induction time, shock-initiation, and the rate of detonation.

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