EXPERIMENTS AND MODELING OF HMX GRANULAR EXPLOSIVES SUBJECTED TO DROP-WEIGHT IMPACT

Yanqing Wu *   Fenglei Huang*

*State key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, 100081, Beijing, P. R. China

INTRODUCTION

The greatest advantages of the drop weight test are flexibility, extended input energy range, simple operation, and the possibility of testing particle beds [1]. Unfortunately, explosive sensitivity rankings from various laboratories do not agree well. A drop-weight impact apparatus equipped with high-speed photography was utilized to examine the initiation mechanisms of several explosives [2]. Optical photographs mainly provide data on the characteristics of burning or explosion sites but cannot directly describe the evolution of hot-spots. Thermal ignition due to a low velocity impact cannot be explained at the macroscopic scale, but rather at the microscopic one [3]. This necessitates more efforts in theory [4] and examining how mechanical energy is converted into localized heat. We first used the drop-weight impact machine equipped with high-speed photographic techniques to investigate the mechanical responses and violent burning of HMX granular explosives at particle level. Based on the experimental design, an analytical model was established through working out kinematic equations coupled with heating equations. Contact plasticity, frictional heating and fracture were considered to be hot-spot sources.

EXPERIMENTAL AND RESULTS

Modified components used by Heavens and Field [5] in a drop weight machine allow high-speed photographic observations of dynamic compression events of explosives. Prior to performing the impact, height of the light source should be adjusted to be aligned with the upper mirror. In the present study, impact responses were photographed at a frame interval of 10 μs, using a low-light-level FASTCAM SA5 LOOOK C3 camera fabricated by Photron Corporation. HMX energetic particles investigated in the present study are in the range of 0.6~1.0m m size (shown in Fig.1), which were prepared by China Academy of Engineering Physics.

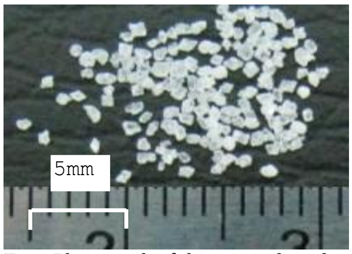


Fig.1 Photograph of the material used for experiment investigation

In Fig.2, when the drop-height increases to 20.0 cm, the formation of a translucent zone can be observed at 620 and 630 μs. The rate at which the hot-spots link together to form an extended reaction front can be very rapid, which is first observed at 640 μs and continues to grow within the following 20 μs. At 670 μs, heat loss played the dominant role so that the burning front began to die out soon as shown in the frame (j). No jetting phenomena along periphery were observed which clearly show the very close relation between mechanical flow of the layer and burning or not. By contrast, localized ejection must be a main mechanism of heat loss for the non-ignition cases in our experiments.

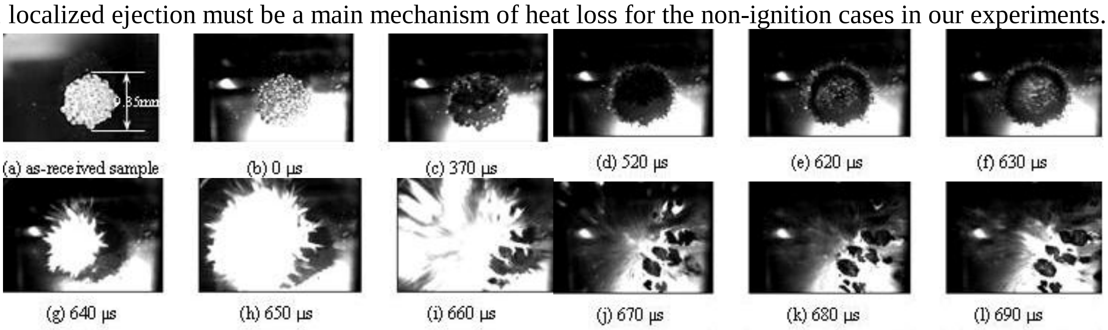


Fig.2 The selected frames from a high speed photographic sequence showing the rapid deformation of HMX particles under 0.20 m-height drop-weight impact, with starting to record time from the instance of contact between the striker surfaces and the particles

MODELING AND RESULTS

Model description

Based on above experimental installation, Fig.3(a) explains the approach for modeling a layer of widely-spaced particles between upper striker and below anvils. Fig.3(b) shows an illustrative graph explaining the contact deformation prior to breakage for an individual particle.

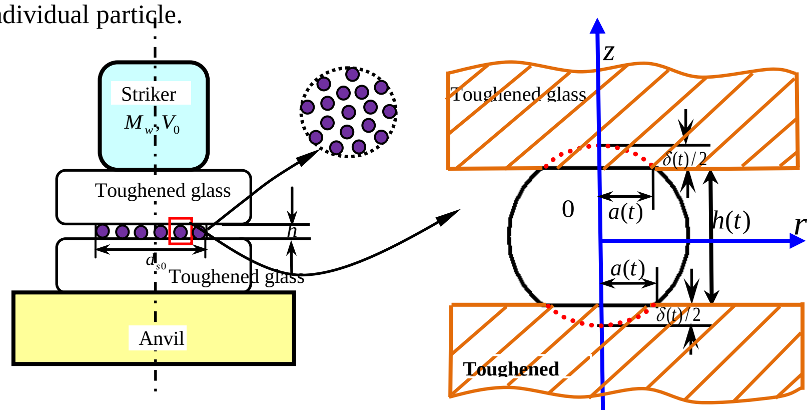


Fig.3 a) simplification of the global loading equipment;
b) partially enlarged detail of deformation quantities of one particle

To simplify the calculations, we assume that the sample consists of a small amount of equal-sized and widely-spaced spherical particles in which the localized ignited sites did not form macroscopic burning fronts. The explosive charge between the flat surfaces is compressed by the upper striker from one direction, whose motion can be determined from its momentum balance.

$$\ddot{z}_u = g - F_c(t)/M_w \tag{1}$$

where z_u denotes the falling distance of the striker, g and M_w are the acceleration due to gravity and mass of drop-weight, $F_c(t)$ refers to the force applied to the drop weight. During the ignition process, the small heated contact zones are assumed to be independent, resulting in a simple thermal condition around the heated contact regions. Temperature rise due to contact deformation, frictional heating [6] and heat of chemical reaction can be obtained by,

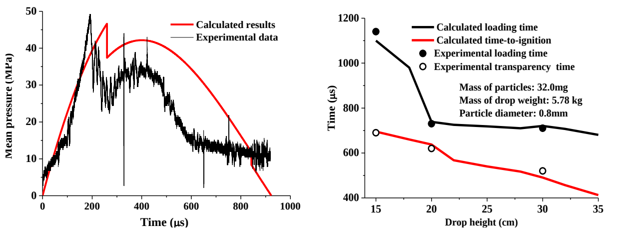
$$\Delta T(t) = \underbrace{\frac{1}{2\rho_s c_s\sqrt{\pi\kappa}}\int_0^{t_{load}} \frac{p_c(t)\dot{\delta}(t)}{(t_{load}-t)^{1/2}}\left\{1-\exp\left[-\frac{a^2(t)}{4\kappa(t_{load}-t)}\right]\right\}dt}_{contact\ \ deformation} + \underbrace{\int_0^{t_{load}} \frac{\mu_f\, p_c(t)v_p(t)}{2\sqrt{\pi\kappa t}}dt}_{friction\ \ heating} + \underbrace{\int_0^{t_{load}} \frac{1}{c} q_r Z_r exp(-E_A/R_g T)\ dt}_{chemical\ \ reaction\ \ heating} \tag{2}$$

where c_s is the specific heat, and κ is the thermal diffusivity constant of the energetic material, t_{load} is the loading time, ρ_s, q_r are the crystal density and the decomposition reaction heat per unit mass of the explosive, and $Z_r\, exp(^{-E}{}_A{}^{/RT})$ is the Arrhenius expression for the reaction rate. p_c is the particle's pressure, $\delta(t)$ is the net impression depth of one particle in contact with the impacting surfaces, $a(t)$ is the contact radius.

Calculated results

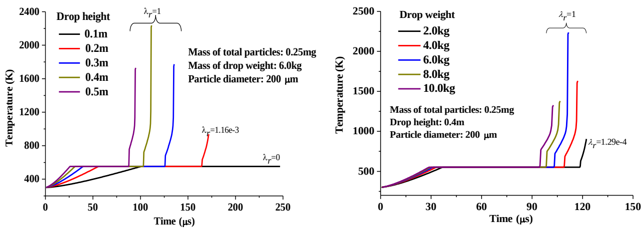
Fig.4(a) compared the calculated mean pressure applied to the effective contact area and experimental measured pressure below the base anvil, for samples of 30.5 mg, 1.2 mm diameter particles impacted by a 5.78 kg drop weight and 20 cm drop height. The half sine wave calculated and experimental results agree quite well qualitatively. A sudden drop in pressure arises from particle fracture. Fig.4(b) compared the calculated and experimental loading time and time-to-ignition. Since the calculated time-to-ignition and experimental transparency occurrence time agree well, local bright spot may mean hot-spot ignition occurrence.

Fig.5 shows the effects of drop height and mass of dropped weight on temperature histories. No ignition takes place in the case of 10.0 cm and 20.0 cm drop-height impacts for samples of 0.25mg total mass and 200μm diameter particles within the impact loading time. The predicted times-to-ignition are 135.5, 111.7 and 95.0 μs corresponding to the drop heights of 0.3, 0.4, and 0.5m, respectively. In Fig.5(b), no ignitions occur for drop weights of 2.0kg, in which the maximum localized reaction fractions calculated approach 1.29e-4. When the drop weights are 4.0, 6.0, 8.0, and 10.0 kg, times to ignition are 117.1, 111.7, 106.6, and 102.6 μs, respectively. The calculated results accord with common experimental phenomena that higher drop height and heavier drop weight increase the probability of explosion. In addition, our calculations show that ignition will occur within 2.3~1.8μs for 0.25 mg total mass and 200μm diameter particles when the impact velocity are in the range 50.0~100.0 m/s. In this case, time-to-ignition is not very sensitive to mass of the dropped weight.



(a) (b)

Fig.4 Comparisons between experimental and calculated (a) average pressure for particles with 1.2 mm diameter and 20-cm drop height; (b) impact loading time and time-to-ignition vs. drop-heights.



(a) (b)

Fig.5 Predictions of temperature histories at the localized contact zones showing the effects of a) drop heights; b) drop weights on thermal responses when keeping other conditions the same.

CONCLUSIONS

Ignition sensitivity of explosives r should be evaluated through combining the photographic observations of deformation and reaction violence information. The experimental results provide very useful data for establishing the theoretical model. The key features of the analytical model is that thermal and mechanical behavior at the particle level, namely, contact deformation and friction, fragmentation resulting from fracture of particles, melting, are considered simultaneously. Computational model with the ability to predict ignition process and mechanical responses efficiently may replace expensive experimental testing.

References

[1] Narayanan S.S.: Single particle breakage test: a review of principles and application to comminution modeling, Bull. Proc. Australas. Inst. Min. Metall. 291: 49-58,1986.

[2] Balzer J.E., Proud W.G., Walley S.M., Field J.E.:High-speed photographic study of the drop-weight impact response of RDX-DOS mixtures, Combust. Flame 135:547-555, 2003.

[3] Barton N.R., Winter N., Reaugh J.E.: Defect evolution and pore collapse in crystalline energetic materials. Model. Sim. Mater. Sci. Eng. 17: 035003-1-19, 2009

[4] Ye S.J. , Tonokura K., Kosh M.: Energy transfer rates and impact sensitivities of crystalline explosives. Combust. Flame. 132: 240-246, 2003

[5] Heavens S.N., Field J.E.: The ignition of a thin layer of explosive by impact. Proc. Roy. Soc. Lond, A. Math. Phys. Sci 338: 77-93, 1974

[6] Carslaw H.S., Jaeger J.C., Conduction of Heat in Solids. Clarendon Press, Oxford, 1959,