High-Rate Mechanical Properties of Energetic Materials

S.M. Walley, C.R. Siviour, D.R. Drodge, and D.M. Williamson

Compared to the many thousands of studies that have been performed on the energy release mechanisms of high energy materials, relatively few studies have been performed (a few hundred) into their mechanical properties. Since it is increasingly desired to model the high rate deformation of such materials, it is of great importance to gather data on their response so that predictive constitutive models can be constructed. This paper reviews the state of the art concerning what is known about the mechanical response of high energy materials. Examples of such materials are polymer bonded explosives (used in munitions), propellants (used to propel rockets), and pyrotechnics (used to initiate munitions and also in flares).

INTRODUCTION

Tens of thousands of papers and reports have been written on the initiation and energy release mechanisms of energetic materials (polymer bonded explosives, propellants and pyrotechnics) since Alfred Nobel took out a patent on dynamite in 1868.[1,2] However, only a few hundred communications have been published on their high rate mechanical properties starting with the work of Hoge in the late 1960s.[3] But since it is increasingly desired to model the impact response of structures containing energetic materials,[4–6] it is of vital importance that constitutive relations be constructed which describe the mechanical response of unreacted energetic materials over the temperature and strain rate ranges of interest[7–9] if meaningful numerical results are going to be obtained for, say, munitions or rockets. With increasing concern about safe-handling, performance during use, changes in properties during storage, and transport of reactive materials, this area is presently amongst the most important in energetic materials research.

DIFFICULTIES OF MODELING PBX MICROSTRUCTURE

How would you…

…describe the overall significance of this paper?

This paper reviews the state of the art concerning what is known about the mechanical response of high energy materials. Examples of such materials are polymer bonded explosives (used in munitions), propellants (used to propel rockets) and pyrotechnics (used to initiate munitions and also in flares).

…describe this work to a materials science and engineering professional with no experience in your technical specialty?

Compared to the many thousands of studies that have been performed over the last century and a half into the energy release mechanisms of high energy materials, relatively few studies have been performed (a few hundred) into their mechanical properties. Since it is increasingly desired to model the high rate deformation of such materials, it is of great importance to gather data on their response so that predictive constitutive models can be constructed.

…describe this work to a layperson?

What happens to an explosive charge when a shell is fired up the barrel of a gun? At present, it is very hard to model this accurately using computer codes. However, it is well known that occasionally guns explode on firing, often killing the soldiers operating them. Thus it is of great importance to have accurate models of the mechanical response of explosives so as to better understand these unwanted events and make them less likely to happen in future.

Many modern energetic formulations are held together using polymer binders giving rise to their common name of polymer-bonded explosives (PBXs). Polymer binders aid both in manufacturing desired shapes and also make such compositions less likely to initiate when being transported or by impact on the battlefield. A typical microstructure is shown in Figure 1. Apart from the differences in size and stiffness of the components, the closest similar common microstructure is concrete. There has thus been some crossover in modeling effort between these two classes of materials.[7]

It can be seen from this micrograph that although one may be tempted to try and model PBXs by microstructures shown schematically in Figure 2, one really needs to be able to handle more irregular particles (shown schematically in Figures 3 and 4). It should be noted that neither Figure 3 nor Figure 4 capture all the features of the microstructure shown in Figure 1, particularly the bimodal nature of the particle size distribution. Bimodal particle distributions are well known to improve the packing density of granular materials.[10–12] This is desirable in PBXs both to maximize the volume fraction of explosive crystals and to minimize the number of pores (which act as initiation sites or hot spots[13–20]). It should also be noted that polymer binders usually contain very small explosive crystals (or fines) which will alter their mechanical properties.[21]

SAFE EXPERIMENTAL TECHNIQUES

All the standard techniques developed over the years for the measurement of high rate mechanical properties of materials have been applied to PBXs. These include split Hopkinson pressure bars (SHPBs)[3,6,22–26] (see Figure 5), Taylor impact[27,28] (see Figure 6), dropweight[23,31,32] (see Figure 7), and shock loading by plate impact[33–39] (see Figures 8 and 9). For a recent overview of these techniques, see the paper by Field et al.[41] Compression experiments are relatively straightforward, but tensile properties have proved more problematical. This is because few labs are set up for machining standard dog-bone tension specimens from these materials. Also such specimens are likely to contain an unacceptably large mass of explosive material to be tested safely. Thus the indirect tension (or Brazilian) test[42] has been used with these materials to obtain both quasistatic[43] and high rate[44] tensile (and hence fracture) mechanical data (see Figure 10b where it can be seen that this test involves compressing a circular disc across a diameter).

Another safe method is to make spec-

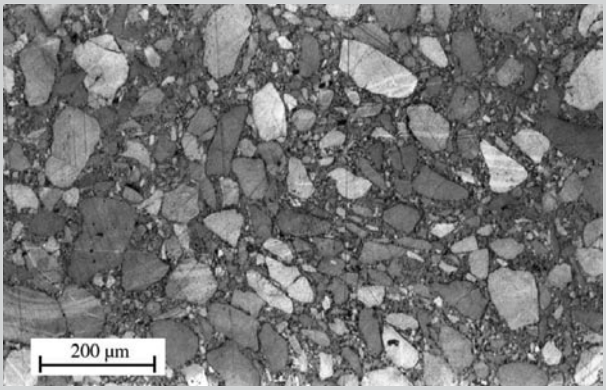


Figure 1. Optical micrograph of a PBX composition. From Reference 8.

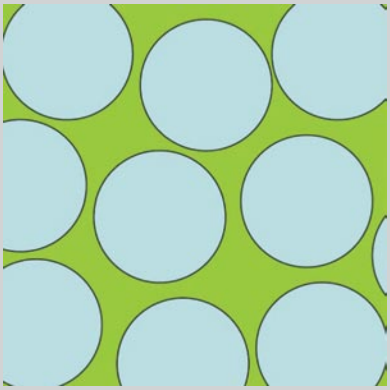
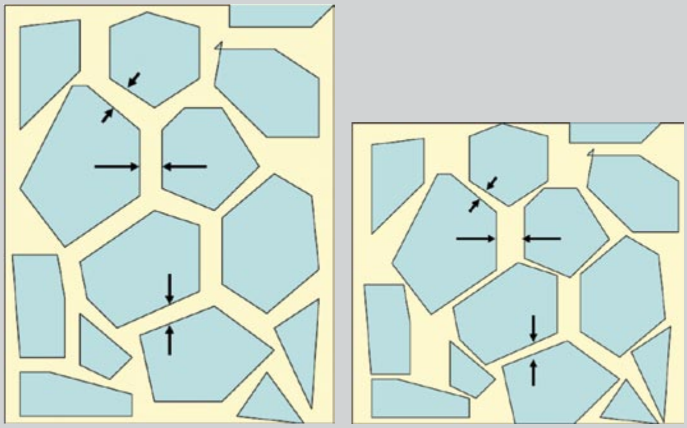


Figure 2. Oversimplified schematic diagram of a PBX where the polymer binder completely fills the spaces between spherical particles.



a

b

Figure 3. More realistic schematic representation of a PBX showing how the explosive crystals may move during compressive deformation from state (a) to state (b).

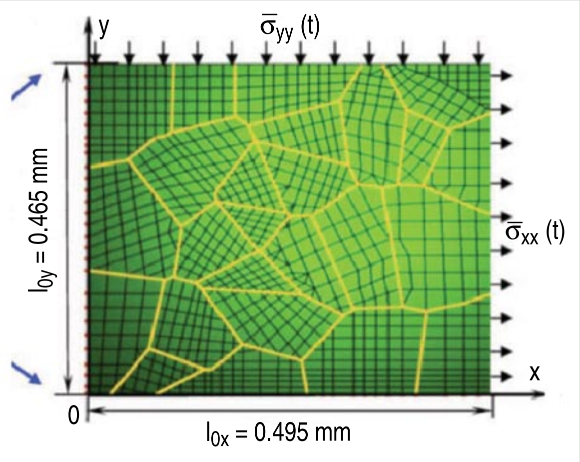


Figure 4. More realistic finite element scheme for a PBX. Adapted from Reference 9.

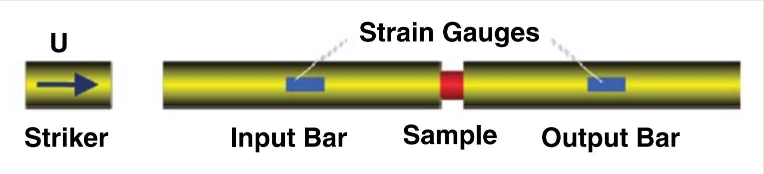


Figure 5. Schematic diagram of a compression SHPB.

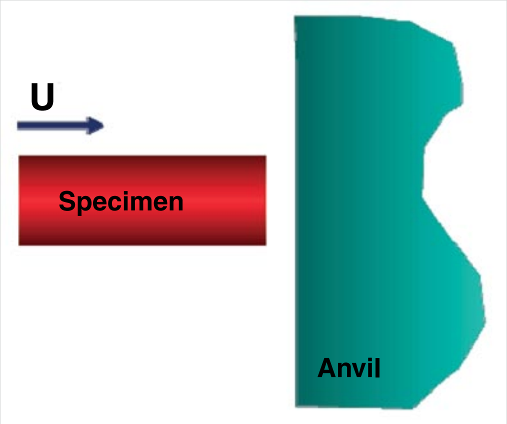


Figure 6. Schematic diagram of classical Taylor impact.[29] In such studies on PBXs the reverse configuration is often used i.e. the anvil is fired at the rod.[30]

Figure 7. Dropweight machine.

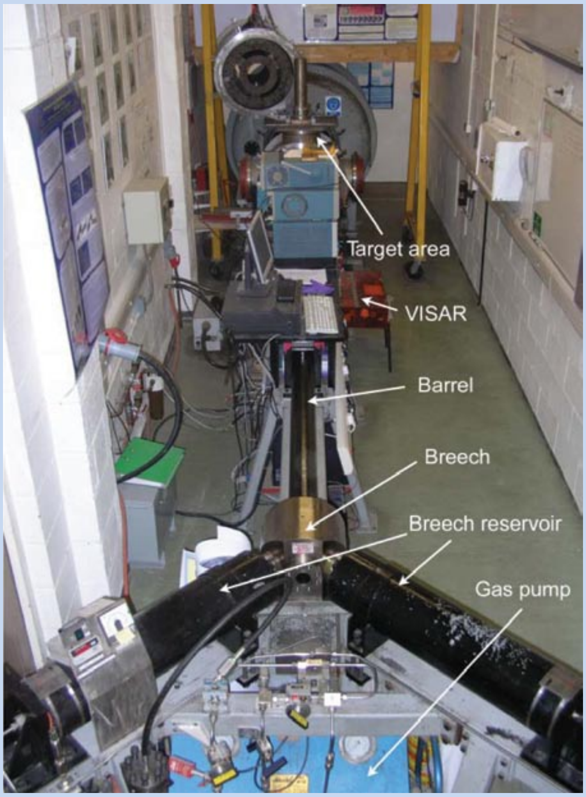


Figure 8. Light gas-gun plate impact facility. For technical details see Reference 40.

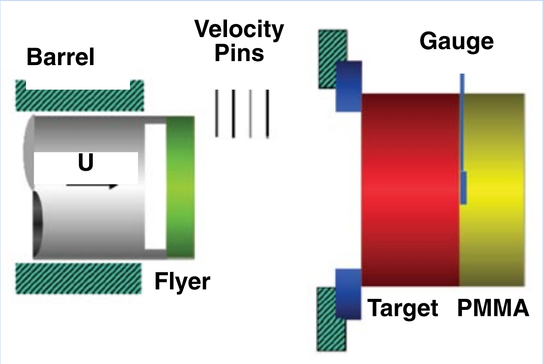


Figure 9. Schematic diagram of a typical plate impact experiment.

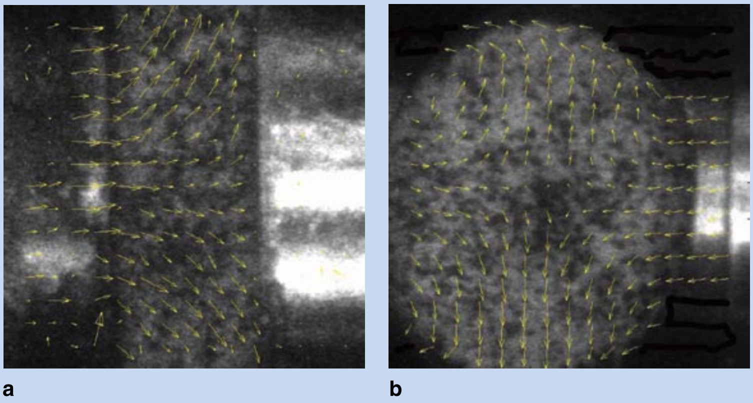


Figure 10. (a) Displacement quiver plot for a PBS compression specimen being dynamically deformed in an SHPB. (b) Displacement quiver plot for a PBS Brazilian specimen being dynamically deformed in an SHPB. From Reference 45.

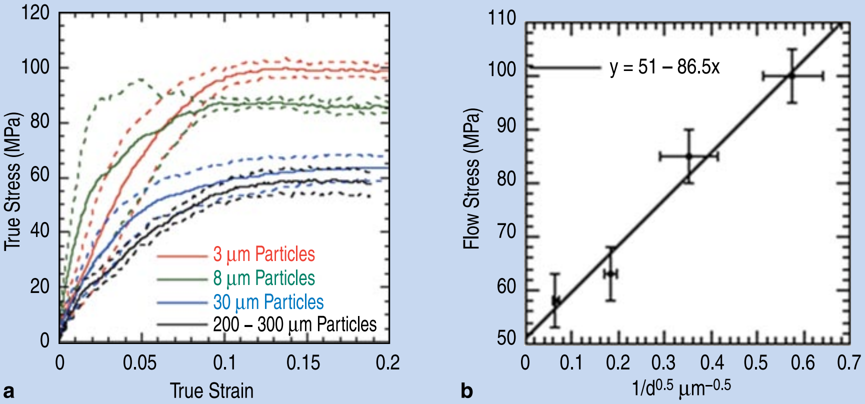


Figure 11. (a) Stress-strain plots for a PBX with different particle sizes deformed using an SHPB at –60°C at a strain rate of ca. 3,700 s–1. (b) Plot of the flow stress versus the reciprocal of the square root of the particle size (same data as shown in (a)). From Reference 49.

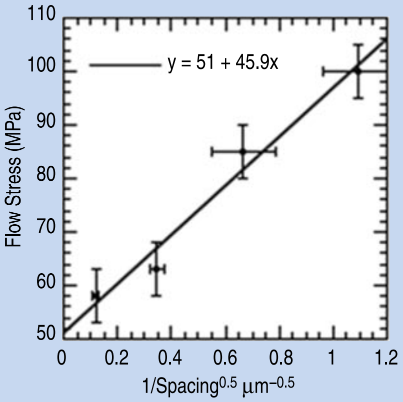


Figure 12. Plot of the flow stress versus the reciprocal of the square root of the particle separation (same data as shown in Figure 11a).

imens from inert crystals with similar mechanical properties to the high explosive but using the same binder. For example, sucrose is used as a simulant for HMX. Such simulants are termed polymer-bonded sugars (PBSs). These studies are particularly useful in the investigation of particle size and particle separation effects on mechanical properties.[46–48] Optical methods have also been found useful to modelers as such methods provide data from the whole surface of a specimen as well as around cracks.[8,43] Examples of the use of optical speckle techniques in the study of conventional compression and indirect tension (Brazilian) specimens deforming in an SHPB are given in Figure 10.

EXPERIMENTAL RESULTS

Interest in particle size effects in PBXs was rekindled by the finding of Balzer and co-workers[49] of a relationship between strength and particle size that was identical in form to the famous Hall-Petch relation for metals[50–52] (i.e., that the flow stress of the material was inversely proportional to the square root of the particle (or grain) size (Figure 10)). This effect was clearly seen at –60°C, but was not so evident at ambient (or room) temperature. Although the relationship between the variables is formally the same, the mechanism must be different as the deformation of PBXs is not governed by dislocation motion. Also it was later pointed out that the flow stress may also be plotted as the same function of particle separation (Figure 11). D.R. Drodge has been performing experiments to separate these two effects as part of his doctoral dissertation.[47]

D.M. Williamson has shown that time-temperature superposition holds for PBXs[23] over a wide range of strain rates and temperatures (i.e., their mechanical behavior is governed by the polymer binder rather than the explosive crystals).

CONCLUSIONS

The high rate mechanical behavior of PBXs has been studied using the same techniques as have been developed for inert materials. For safety, the minimum amount possible of energetic material should be used. Thus, direct tension experiments are not often performed; rather, the indirect (or Brazilian) test method is employed. Optical techniques have proved invaluable in obtaining deformation and fracture data from whole specimens, thus maximizing the amount of information generated for comparison with constitutive models and numerical simulations.

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