

# Particle size effects on the mechanical properties of a polymer bonded explosive

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Two RDX/HTPB polymer bonded explosives (PBXs), with different explosive particle size, were studied in a Hopkinson bar system at three different temperatures. Three temperatures were chosen, two above, and one below, the glass transition temperature of the binder material. The PBX consisted of cyclotrimethylene trinitramine (RDX) crystals in a hydroxyl-terminated-polybutadiene (HTPB) binder. Overall the larger particle sized material was weaker, and exhibited a more distinct yield point than the finer sized material. Both materials showed temperature sensitivity, the effect being greater in the material with the smaller particles. © 2004 Kluwer Academic Publishers

## 1. Introduction

The split Hopkinson bar is a standard apparatus for examining the high strain rate ( $10^3$  to  $10^4$  s<sup>-1</sup>) properties of materials [1]. The recent development of low impedance Hopkinson bars has allowed soft materials with yield stresses as low as 2 MPa to be studied [2]. Importantly, the materials can be shown to be in equilibrium for a useful portion of the test [1, 3]. The importance of checking specimen equilibrium, and using adequate lubrication are recurring themes in the literature, especially when testing such soft materials.

Previous research has shown that the properties of PBXs are a strong function of both temperature and strain rate. The effect of the binder molecular weight on the mechanical properties has also been studied: samples of PBX 9501 were artificially aged to reduce the molecular weight, with no noticeable effect [4].

The effect of particle size on the mechanical properties of PBXs was first observed by Field and co-workers [5, 6]. It was found that increasing the particle size weakens the material. This is a very important parameter for modelling PBXs, and results are presented from experiments on an RDX/HTPB PBX with two different particle sizes.

## 2. Experimental

### 2.1. Materials

The materials investigated were designated RF 38-09 and RF 38-22, manufactured by RO Defence, Glascoed. Both materials are polymer bonded explosives consisting of 88% cyclotrimethylene trinitramine (RDX) and 12% hydroxyl-terminated polybutadiene (HTPB). RF38-09 has a median RDX particle size of 710  $\mu\text{m}$ . RF38-22 has median particle diameter of 159  $\mu\text{m}$ .

### 2.2. Sample preparation

The materials were supplied as cylinders of 100 mm diameter and 50 mm thickness. From these, 2 mm thick

strips were cut. Discs of 6 mm diameter were punched out from these strips. Since the preparation process did not produce samples of exactly reproducible size, each sample was individually measured. All samples were checked carefully to ensure that they had parallel faces.

A difficulty in sample preparation was the dropping out of explosive crystals from the polymer binder, as they were easily brushed from the surface of samples. This was especially a problem with the RF 38-09 material, as the loss of large surface particles produced voids on the surface, making the surface porous and significantly reducing the number of particles in the specimen. Care was taken to reject specimens that had lost surface particles.

### 2.3. Apparatus

The Cavendish SHPB uses 12.7 mm diameter input and output bars, which are approximately 0.5 m long. These are instrumented half-way along their length with Kulite type AFP 500-09 silicon strain gauges. A loading pulse is induced in the input bar using a striker propelled by a light gas gun.

At the sample, the incident wave splits into a reflected wave, which travels back down the input bar, and a transmitted wave, which travels on through the output bar. The strain pulses measured in the two bars are analysed using the standard Hopkinson bar equations to generate stress-strain curves [1]. When testing low impedance samples, such as polymers, the transmitted wave is often very small, and difficult to measure. The transmitted signal can be increased by reducing the mismatch between the impedance of the bar and specimen, by, for example, using low impedance metal, or even polymer bars. Unfortunately polymer bars are visco-elastic, and therefore highly dispersive, making calculations of material properties more difficult, since the waves change shape between the sample and the strain gauges [7]. Analytically it is more straightforward to use low impedance elastic metal bars. Bars

instrumented with semiconductor strain gauges are able to detect very small forces: for example magnesium alloy bars have been used successfully to measure stresses of just 1 or 2 MPa.

## 2.4. Technique

Magnesium alloy bars were used to test the two PBX materials at ambient temperatures, at a strain rate of approximately  $5000 \text{ s}^{-1}$ . Samples were lubricated using paraffin wax, which has been shown to eliminate friction for polymer specimens [8, 9].

Experiments at non-ambient temperatures were carried out using Inconel bars. To do this the sample and bar ends were enclosed in an environmental chamber. The mechanical properties of Inconel change less than for most other metal alloys over a temperature range of  $-200$  to  $+600^\circ\text{C}$ . It has been shown that elastic waves pass undistorted through a region of the bar in the temperature range  $-150$  and  $+500^\circ\text{C}$  [10, 11]. This means that tests on hot and cold samples can be performed by heating or cooling the sample, and the ends of the Inconel bars, without needing to compensate for the effects of the temperature gradient on the elastic waves in the bars.

For low temperature experiments, the chamber was cooled using helium, which had been passed through a coil immersed in liquid nitrogen. For high temperature experiments, the chamber was heated with a hot air gun. The temperature was measured using chromel-alumel thermocouples (accurate to  $\pm 1^\circ\text{C}$ ) attached to the Hopkinson bar. Between five and 10 min were allowed for the sample to reach thermal equilibrium. This was found to be sufficient time for equilibrium using a thermocouple inserted in a test specimen.

## 3. Results

Hopkinson bar results are only valid if the sample is in stress equilibrium. This is usually checked by comparing the one and two wave analyses [2]. The one wave analysis uses the transmitted wave to calculate the force on the specimen, whilst in the two wave analysis this force is calculated from the incident and reflected waves. If the sample is in equilibrium these will give the same result. In these experiments, the transmitted wave was so small that it was impossible to use the 2-wave analysis on the data, the noise on the incident and reflected waves being larger than the size of the transmitted wave. Instead, discs of pure HTPB were tested with two PVDF stress gauges, one on each side of the sample, between the sample and the bars. The voltage outputs from the stress gauges were scaled using their calibration factors, and are compared in Fig. 1. The HTPB samples, which are softer than the PBXs, are in equilibrium within  $10 \mu\text{s}$ , so the stress-strain curves are certainly valid after this time, which corresponds to a true strain of approximately 0.05 in the PBX samples. Separate HTPB samples were used because the chamber used to warm the PBX samples did not allow the PVDF gauges to be inserted. Fig. 2 shows the stress strain curve for the HTPB. The degree of cross-linking may not be the same in these samples of HTPB as the

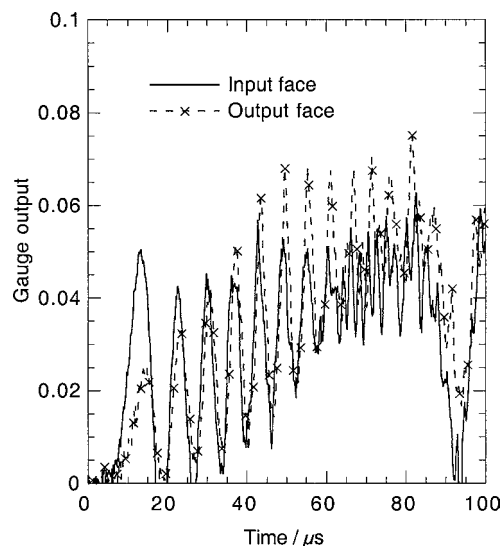


Figure 1 Comparison of stress gauge values on HTPB specimen. The gauges have the same output, so the stresses on the front and rear faces of the specimen are the same, after about  $10 \mu\text{s}$  of loading.

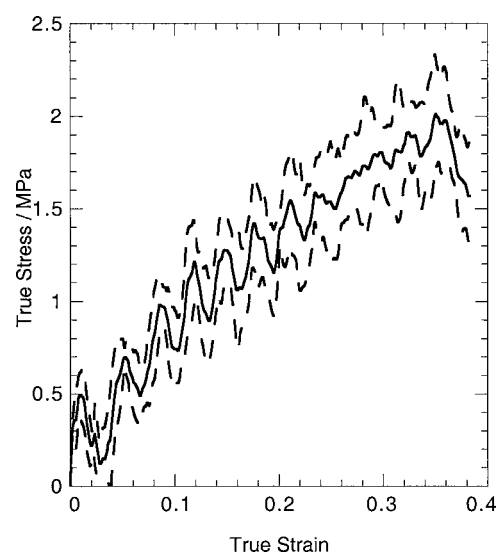


Figure 2 Stress strain curve for HTPB at  $5000 \text{ s}^{-1}$ , showing mean and standard deviation from 6 tests.

HTPB binder in the PBX, so the stress strain curves should be compared with this in mind.

If a true bulk material property is being measured, sample size should not have an effect. It is generally accepted that a sample containing of the order 1000 particles will represent the bulk material properties [12]. This is the case for the RF 38-22 but not for the RF 38-09. However, if the samples were not representative of the bulk a large variation would be expected between individual specimens, due to irregularities in particle distribution or orientation. As this is not seen, it is thought that the specimens are representative of the bulk material.

### 3.1. Room temperature ( $25^\circ\text{C}$ ) studies

Fig. 3 shows stress strain curves for samples of RF 38-22 and RF 38-09. The RF 38-22 (smaller particle size) material showed continual strain-hardening throughout the loading. The RF 38-09 material showed

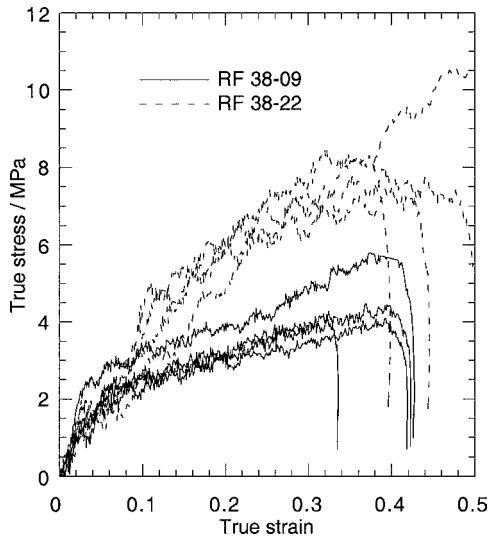


Figure 3 Stress-strain curves for RF 38-22 and RF 38-09 at room temperature and  $5000 \text{ s}^{-1}$ . The RF 38-09, which contains the larger particles, exhibits a more distinct yield point.

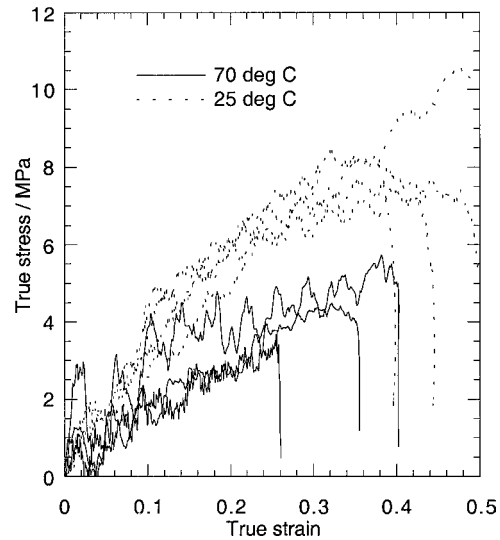


Figure 5 Stress-strain curves for RF 38-22 at 70 and  $25^\circ\text{C}$ , showing the decreased strength of the material, and also the increased noise due to the use of higher impedance Inconel bars.

some strain-hardening at high strains, but it also yielded at a true strain of approximately 5%, around the point when the data become valid. It is important to remember that the Hopkinson bar technique cannot determine the initial elastic properties before yield as the sample has not yet reached equilibrium for these small strains.

### 3.2. Low temperature studies

The samples were cooled to approximately  $-100^\circ\text{C}$ . Results are shown in Fig. 4. Both types of PBX shattered in a brittle manner, and so did not conserve volume after fracture. Because of this, engineering stress is shown against time.

### 3.3. High temperature studies

The samples were heated to  $+70^\circ\text{C}$ . The stress-strain curves for the two materials are shown in Figs 5 and 6. The curves are very noisy, since the transmitted signals

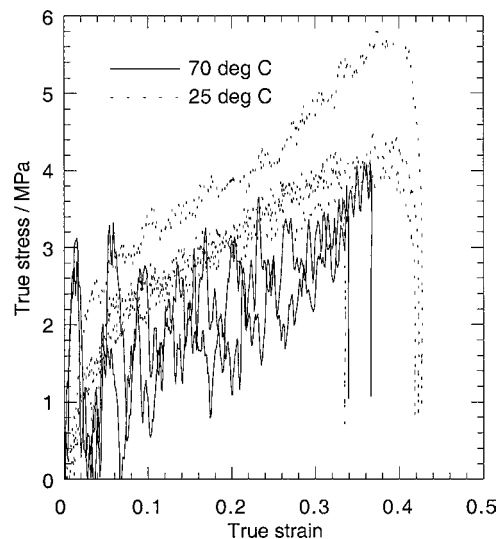


Figure 6 Stress-Strain curves for RF 38-09 at 70 and  $25^\circ\text{C}$ .

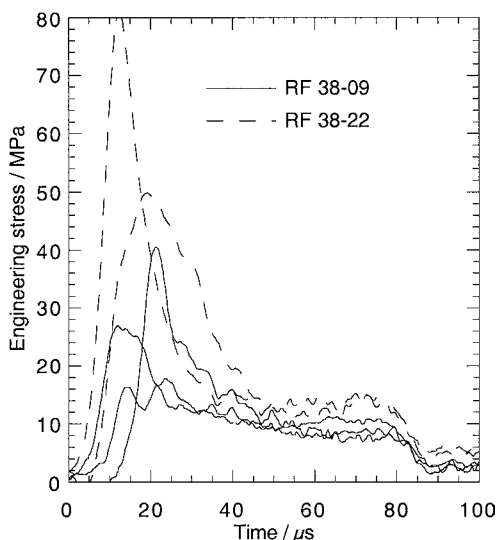


Figure 4 Stress-time curves for RF 38-22 and RF 38-09 samples at  $-100^\circ\text{C}$ . The samples fail after about  $20 \mu\text{s}$ , before settling to a plateau, which is slightly higher for the smaller particle size RF 38-22.

were small, only a few mV in size, the weakness of the materials being compounded by the use of high modulus Inconel bars. The impedance of the Inconel used was  $41,200,000 \text{ kg m}^{-2} \text{ s}^{-1}$ , whilst that of the Magnesium alloy was  $8,810,000 \text{ kg m}^{-2} \text{ s}^{-1}$ .

## 4. Discussion

A comparison of the two materials is shown in Fig. 3. It can be seen that the RF 38-22 deforms at a higher stress than the RF 38-09, does not have a distinct yield point, and also strain hardens more rapidly. Failure paths in PBXs tend to run along the long edges of the explosive filler, and avoid regions of fine filler and binder [13], so it is expected that the larger particle size material will be weaker, as the available paths for fracture are longer.

In the low temperature experiments, both materials shattered at a high stress, before settling down to a consistent flow stress. The glass transition temperature of HTPB is approximately  $-65^\circ\text{C}$ . Since the PBX's mechanical properties are dominated by the binder,

the PBX also becomes brittle below this temperature. The stress of the initial peak is not reproducible, as it depends on the pre-existing flaws in each sample. Sample 3 of the RF 38-09 material shows evidence of failure due to crack formation, before hardening again. The later part of the stress curve is probably governed by the strength of the mixture of binder material and crystals. This section is slightly higher for the RF 38-22 material.

Figs 5 and 6 compare the room temperature and high temperature results. The RF 38-22 shows a greater dependence on temperature than the larger particle size RF 38-09. This indicates, as expected, that the properties of the larger particle size material depend to a greater extent on the crystal particles than the smaller particle size material, since the mechanical properties of the polymer are more strongly dependent on temperature than those of the explosive crystals.

## 5. Conclusions

The research presented here indicates that changing the particle size in the PBX can affect both the strength of the material, and the shape of its response to high strain rate loading. The strength decreases with increasing particle size. Increasing the temperature of the material also decreases its strength, but not the nature of its response. The temperature effect on larger particle size materials is smaller, which is expected because the larger particle size material is governed to a greater extent in its mechanical properties by the relatively temperature insensitive explosive crystals.

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