High-Rate Experiments on a Nitrocellulose/Nitroglycerine Propellant

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Abstract. The mechanical behaviour of a rubbery nitrocellulose/nitroglycerine double-base propellant was probed at a range of strain rates. The propellant was relatively soft, and inhomogeneous on the millimetre scale, presenting a few experimental difficulties. These difficulties were overcome in a shock experiment using a plate reverberation technique. The resulting information on the shock Hugoniot and release isentrope of the propellant was compared against a hydrocode using a group interaction based material model.

INTRODUCTION

Nitrocellulose/nitroglycerine (NC/NG) double-base propellants are a major component of some solid rocket motors. Solid rocket motors are vulnerable to a phenomenon known as unknown-to-detonation transition (XDT). In XDT, a fragment striking a rocket motor initiates detonation of the motor after a short delay [1].

The mechanical properties of a propellant at high rate will directly influence its XDT response. A physically-based material model for the propellant is valuable for predicting these properties in the hot, highly-strained material that contributes to XDT. An NC/NG propellant is essentially a plasticized polymer. For such materials, group interaction modelling (GIM) [2] is a useful approach to material modelling.

This work consists of high-rate experiments on an NC/NG propellant, probing both singly-shocked and off-Hugoniot states. The results are compared to the predictions of a GIM model for the same propellant.

This work was part of the Insensitive Munitions for Rocket Motors (IMRM) programme of the Weapons Science and Technology Centre (WSTC) of the UK Ministry of Defence. IMRM aims to develop an understanding of XDT in rocket motors and the role of propellant properties in the observed responses to fragment impact. The University of Cambridge was a partner in this programme, led by QinetiQ and including Imperial College London and Roxel Ltd.

METHOD

Experimental

To exercise the model, it was desirable to probe off-Hugoniot states. A reverse-impact plate reverberation technique provides information on a single shocked state and several points on the release isentrope from that state, in a single experiment [3].

As a cast double-base propellant, the material under investigation has some heterogeneity on the millimeter scale [4]. However, the plate reverberation technique has been used successfully on concrete, a much more heterogeneous material [5]. Plate reverberation is therefore likely to be usable here.

Figure 1 shows the layout of the experiment. The projectile was launched using the single stage 2″ light gas gun at the Cavendish Laboratory. Rear-face velocity was recorded using a three-point push-pull VISAR [6, 7]. Measurement points were positioned on the experiment axis, 12 mm above the axis, and 12 mm right of the axis. These three measurement points served three purposes. First, the arrival time of the initial shock at each point indicated the angle

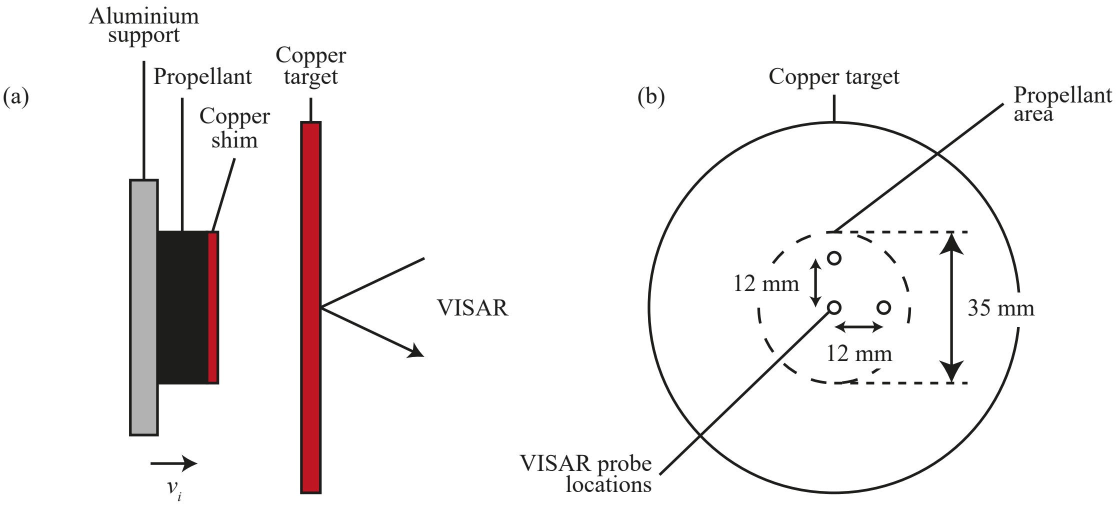

FIGURE 1. Layout of plate-reverberation experiment. Not to scale. All measurements approximate; precise measurements varied between experiments. (a) Side view. Aluminium support 3 mm thick Al-6082 alloy, propellant 5 mm thick, copper shim 25.4 µm thick C101 high conductivity copper, copper target 1 mm thick C101 high conductivity copper. Propellant glued using Ottocoll P520 two-part polyurethane cement. (b) Rear view, showing VISAR probe locations.

of that shock relative to the target plate. This in turn allowed the angle between the projectile and the target plate to be calculated. Second, the separate measurement points provided an assessment of the effect of material heterogeneity. Third, the off-axis points are affected by lateral release during the experiment, providing a further probe of the material model.

Figure 2 illustrates the propagation of shock and release waves in this experiment. The thin target plate experiences multiple shock-release cycles before the initial shock has propagated through the thicker propellant sample. Each release probes a single point on the propellant's release isentrope: the odd-numbered states in Fig. 2b. The even-numbered states are directly observed by the VISAR. The two sets of states are coupled by the loading and unloading curves of the copper target plate.

Modelling

Group interaction modelling was used to construct a material equation of state, constrained by dynamic mechanical analysis (DMA [8]) of the propellant. A constitutive model was constructed from quasi-static cyclic tensile testing of the propellant at temperatures from −30 °C to 20 °C.

The equation of state and constitutive model were used as input for GRIM, an Eulerian hydrocode. GRIM's numerical scheme cannot accommodate polymer relaxation. Relaxation was therefore neglected. Existing material models for the copper, aluminium and glue were used.

RESULTS AND DISCUSSION

Figure 3 compares the experimental results for the central VISAR probe with model predictions for the same location, ignoring the glue layer. Agreement is quite close early in the experiment. The simulation shows a slightly stiffer material response than experiment, which is an expected consequence of GRIM's inability to model relaxation. This lack of relaxation also contributed to a higher propellant shock velocity in simulation than in experiment, shown by the early arrival of the reflected shock from the aluminium back plate.

Later, model and experiment begin to diverge. At this stage in the simulation the propellant experiences tensile load, and fails. The fall in reported velocity corresponds to the strength of the propellant. The most likely reason that this is not observed experimentally is that some other interface in the experiment, with negligible tensile strength, fails. The most likely candidate for this is the interface between the copper shim and the copper target.

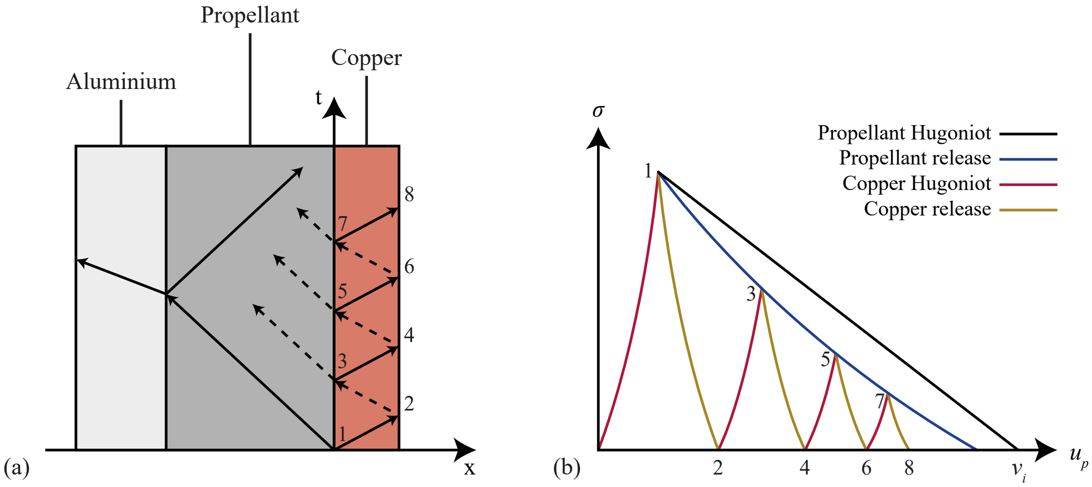

FIGURE 2. Shock propagation in the plate-reverberation experiment. (a) As an *x*-*t* diagram: solid lines are shock, dashed lines are release. (b) Illustrating stress vs. particle velocity relationship.

Interestingly, while the timings and levels of the velocity plateaux show good agreement between model and experiment, the evolution of their gradients does not.

While agreement between model and experiment is good in the early stages of the experiment, it is during these stages that the hitherto-neglected glue layer has the most influence. Figure 4 shows the effect of modelling the glue layer on the two higher-velocity experiments. Agreement in the plateau velocities is noticeably improved by modelling the glue. However, in the experiment at $713\,\mathrm{m\,s^{-1}}$, the model diverges from the experiment after only three plateaux (state 6 in fig. 2). This divergence remains unexplained.

Off-axis effects

Figure 5 shows the output of all three VISAR measurement points in a single reverberation experiment. The most obvious feature is the spread in shock arrival times. This corresponds to an angle of 8.1 milliradians between the normals to the flyer and the target plate. In subsequent experiments improved alignment procedures reduced this misalignment to between 1 mrad and 2 mrad.

It is also interesting to note that the reported velocity at the off-centre points, while initially matching that in the central point, falls off over time. This almost certainly corresponds to lateral release from the edge of the propellant sample. Unfortunately, while the relative position of the three measurement points was well-known, the offset between the central measurement point and the centre of the propellant sample was not well constrained. This complicated comparison between the off-centre probe points and simulation.

CONCLUSIONS

Plate reverberation is a useful experimental tool for testing the high-rate behaviour of material models, provided the model for the target plate material is already well-validated.

A group interaction model for high-rate material behaviour of the NC/NG propellant under investigation could be constructed and parameterized using only dynamic mechanical analysis and quasi-static tensile experiments.

The predictions of the group interaction model matched the results of the plate reverberation experiment well.

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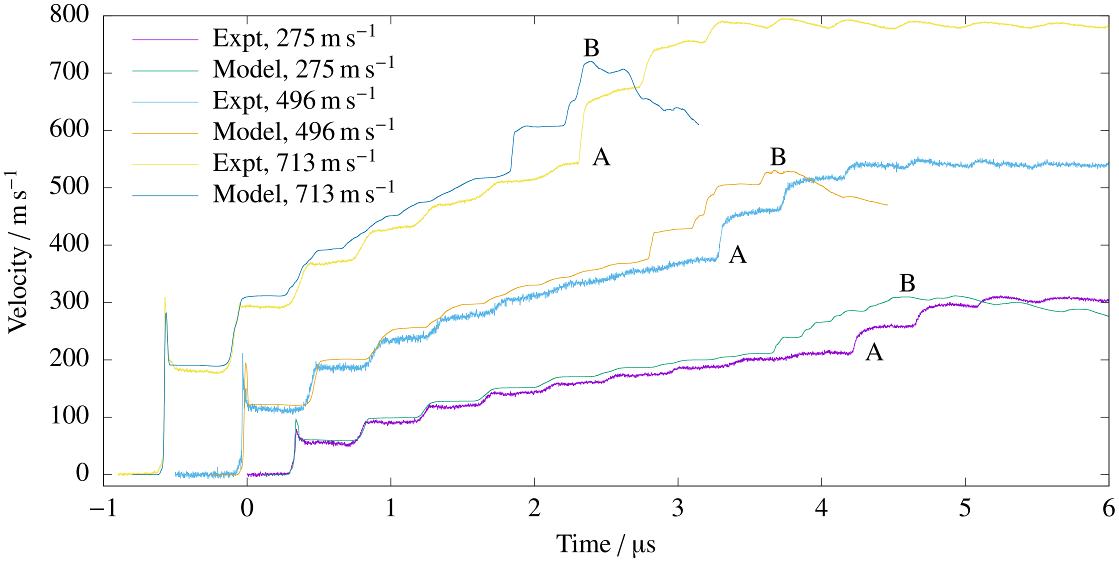

FIGURE 3. Results, experimental vs. modelling, centre probe, no glue. Data time-shifted to separate traces. Note arrival of reflected shock from aluminium support (A), and breakdown of model (B).

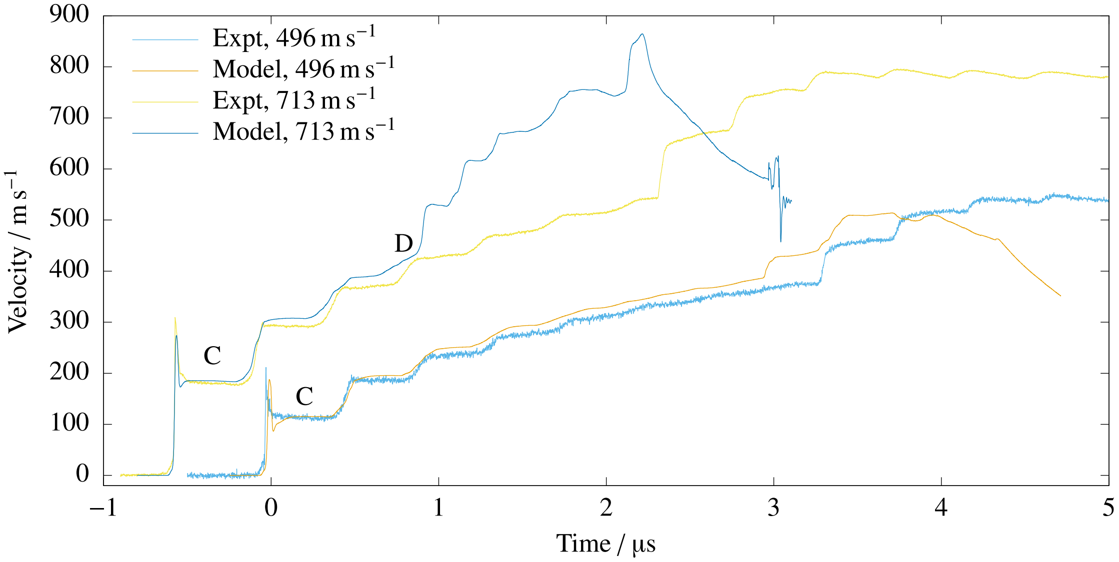

FIGURE 4. Results, experimental vs. modelling, centre probe, glue layer simulated. Data time-shifted to separate traces. Note agreement in first plateau level (C) and rapid divergence of model and experiment for higher-velocity data (D).

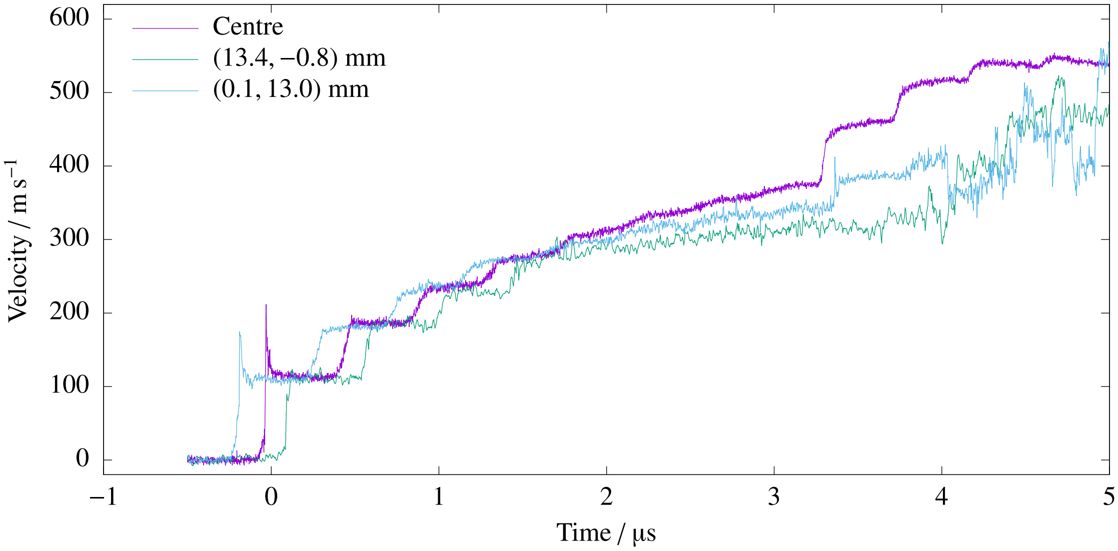

FIGURE 5. Output of all three VISAR probes in experiment at 496 m s^{-1}. Note different shock arrival times due to impact tilt. Poor signal-to-noise after approx. 3 µs makes interpretation of off-centre gauges uncertain past that time.

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