IM Rocket Motor Design & Assessment Toolset – phase 1

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Agenda

1. The Problem
2. Programme Aim
3. Strategy & Approach
4. Material
5. Material Algorithm Development
6. Small Scale Testing
7. Energetic Response Model
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The Problem
1 The Problem

There is a requirement for the UK to both be able to design and manufacture IM rocket motors and assess foreign rocket motors for in-service use under a wide range of conditions. Missile systems used in current operations theatre are vulnerable to bullet and fragment impact. In many cases this is due to shock initiation of detonation of damaged propellant spalled across the central bore of the rocket motor (XDT).
The Problem

The objective of this requirement is to develop, demonstrate and validate a predictive modelling capability for the hazard response of rocket motors, with a particular emphasis on XDT, as part of an improved time and cost effective IM certification process for rocket motors.

Possible responses:

SDT: Shock to Detonation Transition.
The shock generated by the fragment impact is strong enough to generate a prompt detonation.

DDT: Deflagration to Detonation Transition.
The shock generated by the fragment impact initiates burning which transitions into a detonation after the shock has travelled a finite distance into the explosive.

XDT: Unknown Detonation Transition.
The fragment impact fractures the energetic material and projected debris ignites and burns violently/detonates when it strikes a solid surface.
Programme Aim
2 Programme Aim

AIMS

• The aim of the programme is to address the development of an ability to design, qualify and certify a rocket motor that is resistant to XDT with an optimised, timely and cost effective limited series of small scale tests, supported where necessary by numerical simulation and material testing.

• The programme elements include:
  – Understand Materials - Application of existing material science-based methods to predict the fracture, ignition and burning behaviour of highly damaged energetic materials.
  – Test - Model characterisation against small scale instrumented experiments:
  – Develop a predictive modelling capability validated against large scale, system level tests.
  – Integrate with the related research programmes to understand and define ageing effects, and the wider Smart Certification programme;
  – Update and apply the IM assessment protocol
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Strategy & Approach
3 Strategy & Approach

- Importance of damage on burning behaviour
- Conditions for ignition
  - Violence of the burn?
Material
4 Material

Propellant (Elastomer Modified Cast Double-base propellant- EMCDB) contains nitrocellulose, nitroglycerine and a nitramine (RDX)

- In service rocket motor propellant.
- Extensive data and experience of its behaviour.
- We need to develop a material model to describe its thermo-mechanical properties and behaviour.
- Also tested precursor propellants to provide a generalised understanding of the role of additives and particulates on thermo-mechanical properties and behaviour.
- Provides the potential to predict ‘min smoke’ and role and level of nitramines in controlling the violence of any response.
- Provides double base propellant design and assessment capability.
4 Material

Material Tests performed by Cambridge and QinetiQ

- Tests
  - Dynamic Mechanical Thermal Analysis (DMTA)
  - Compression Tests
  - Damage Tests
  - Small Scale Impact Testing
  - Fragmentation Testing
  - Burn Rate Measurements
  - Thermal Properties
  - Plate Impact
  - Tensile Samples JANNAF
4 Material

Integrated Modelling-Experiment methodology.

- Numerical simulation capability based on several integrated semi-empirical models:
  - Experiment measures properties to give the constitutive model for the specific propellant;
  - Allows simulation of integrated experiments and prediction of response of the rocket motor;
  - Analytic model for mechanical response predicts behaviour;
  - Feeds into semi-empirical capability at various stages including burning.

- Validated by experiments on propellant.

Exploitation.

- Gives capability to determine constitutive response of other similar compositions with minimal further experimental measurement.
5

Material Algorithm Development
5 Material Algorithm Development

Nitrocellulose (NC)

• Structure and existing data reviewed.
• Basic model developed using Group Interaction Model (GIM).

• Research addressed the additional data required to demonstrate the ability of the model to describe the deformation mechanisms and properties and how they are based on the constituents and microstructure.
• Developing a method to describe the observed statistical variation in nitration level and its importance for mechanical properties and subsequent processing requirements.
• Will provide an ability to assess different sources/batches of nitrocellulose and ultimately reduce the demands for re-qualification.
5 Material Algorithm Development

NC

• GIM parameters associated with microstructural components that can vary due to processing or molecular architecture.

• Identified 11 checks against measured behaviour/properties to confirm structure (e.g. nitration level) and validate the model.
  
  − Checks include solubility, loss tangent, cross linking, vibration spectra, specific heat, thermo-mechanical properties.
  
  − Roxel will identify/agree most appropriate from a manufacturing perspective.
5 Material Algorithm Development

Nitroglycerine (NG)

• Structure and existing data reviewed.
• Basic model for solid developed using GIM.
  − Potential interactions when nitroglycerine is used to gelatinize
    nitrocellulose requires parameters for solid nitroglycerine.
  − Requires latent heat of fusion for prediction/validation of liquid properties.
• Allows study/prediction of properties of NG:NC mixtures with different levels of NG infiltration.
• Allows interpretation of propellant response following different manufacturing routes as NG sees
  different environments in separate parts of the composite
  − Detectable in DMA
5 Material Algorithm Development

Prediction of Roxel Propellant A DMTA

This prediction required specific assumptions to be made as to how the NC and NG were distributed within the propellant

- Subsequently confirmed by Roxel
- Would vary with NC type and content
- Would vary with age

- Gives the ability to assess propellant components and give quantitative information at an early stage in the production process
- Leads directly to prediction of propellant properties
5 Material Algorithm Development

Equation of state predicted from composition

- Understanding the microstructural composition of the propellant allows prediction of the mechanical properties although the propellant behaviour is likely to be complex.

- It will act as a composite material at several levels: by action of the particles in the RDX and by action of the areas with less NG. This complexity can be seen in the Hugoniot data, particularly when compared to the predictions.

- The Stress Hugoniot prediction is very good.
5 Material Algorithm Development

Equation of state predicted from composition

- The shock – particle velocity relationship is not predicted very well on two counts:
  - it is a different shape
  - it deviates significantly at high particle speed.
- The data on shock speed curves upwards – a behaviour not normally seen in materials – and this suggests that the material changes somehow when exposed to the more severe conditions. Currently this is thought to be due to the ‘free’ NG interacting with the underlying composition structure.
5 Material Algorithm Development

Constitutive model

- Porter-Gould format
- Fraction of filler particles not equivalent to previous compositions for which this has been successful. Assumed Propellant A would act as if it were a particulate composite material.
- Nitramine particles in the propellant would stiffen the NC/NG binder.
- Input mechanical work, would debond through a normal damage process, reducing the modulus of the propellant.
- Not the case under most conditions.
- Only one condition suggestive of this behaviour.
Constitutive model

- Data analysis showed generally the shape of stress-strain curves different to the Porter-Gould constitutive model.
- Behaviour typical of a rubbery polymer.
- Volume fraction of particles in the composite is too low to dominate behaviour.
- Behaviour best described as linear viscoelastic with strain stiffening as is normally seen in rubbers.
- Peak stress is reached when the pellets start to debond from one another.
- Different tensile and compression test behaviour
- Needs better implemented polymer model in numerical simulations.
6

Small Scale Testing
6 Small Scale Testing

Fragmentation

- Explosively launched sphere
- Propellant sample
- Flash array
- Diffusing screen
- High speed video camera
- Box PMMA or Polycarbonate
- Cotton cloth
- Foam
- Simona plastic sheet
6 Small Scale Testing

Fragmentation
Round 3 Velocity=\sim 750\text{m/s}

Impact Crater

Fragment Size Distribution

Debris Cloud

Particle Size Distribution by Volume

Circle Equivalent Diameter [\mu m]
6 Small Scale Testing

Fragmentation predictions based on microstructure of composite propellant and manufacturing route

- Model based on two lengthscales at which fragmentation can occur
- Size distribution captured reasonably well.
- Some obvious mismatches but a consistent argument can account for them.
- Largest number of fragments in the predicted distribution is from single black pellets.
- If black pellets were found to have fragmented further then they would tend to only fracture into a few fragments, increasing the number of fragments in the range 500 – 1000 microns, and reducing the numbers at 1000 – 2000 microns.
- Fragmentation of the black pellets could occur due to the impact shock as their loss mechanisms should be suppressed in this short time.
6 Small Scale Testing

Ignition

Round 7: Velocity=\(~950\text{m/s}\)
6 Small Scale Testing

XDT

Round 1714F16: Velocity=~1370m/s
7

Energetic Response Model
7 Energetic Response Model

- Solid Material Model
- EoS
- Constitutive Damage
- Fracture

- Products
- EoS
- CHEETAH

- Ignition
- Burning

- CHARM
- EoS
- Temperature
- Hotspots
- CHEMISTRY

- GRIM

- DYNA

- XDT Problem
- Rocket Motors
- Shaped Charges
- Warheads
7 Energetic Response Model

- Ignition & Burning
  - We require complete Equations of State (EoS) for the unreacted propellant and its reaction products.
  - Porter-Gould Damage model description of hotspot term integrated into CHARM.
  - Validation not completed.
7 Energetic Response Model

Progress

- Idealised cloud impact to demonstrate functionality.
- Reaction delay of \(~3\mu s\).
- Retonation reaches main charge by \(10\mu s\).
- Main charge detonates – over by \(15\mu s\).
- Minor developments remain.
- Model must be able to predict the experimental observations.
Model Validation
8 Model Validation

Model must be able to reproduce a number of important features in the bulk response of the propellant.

Impact Plume

Debris cloud shape
And concave specimen edges

Axial plume ejection
8 Model Validation

Progress

- Model implemented in GRIM & DYNA.
- Damage limiting
  - No plume
  - Curved edges
  - Good debris cloud shape
- No damage limiting
  - Very good plume
  - No edge curvature
  - Wrong cloud shape

\[ V = 1009 \text{ m/s} \]

Damage Limiting

ON

OFF
8 Model Validation

Progress

- Resolution study – with damage limiting

V=1009m/s
8 Model Validation

Progress

- Resolution study – with damage limiting
- $V=1009\text{m/s}$

Baseline  Refinement 1  Refinement 2
8 Model Validation

Progress

• Resolution study – comparison with experiment (V=1009m/s)
Conclusions
9 Conclusions

Fundamental Understanding

• Material characterisation has achieved a significant improvement in understanding the constitutive response of double base propellants.
• Established a methodology for testing other propellants of this type.
• Demonstrated the very different deformation response of these materials compared to a PBX and role of NG in modifying this response.
• Material science based methods can predict many of the properties of double base propellants, including understanding the role of the interaction of NG with NC.
• Ability to predict other NG-NC based propellants represents a significant achievement.
• The semi-empirical polymer model, however, cannot predict the observed deformation behaviour across the full strain rate regime. Needs the implementation of the complete polymer model in a new numerical scheme.
• The ability to predict the properties of NC, based on its structure, allows the development of a simple small scale screening test to determine the suitability of a new source of NC. This has significant potential in reducing re-qualification of new sources of NC.
• Cost effective and game changing approach.
9 Conclusions

Small Scale Testing

- Small scale fragmentation soft recovery experiment has achieved a UK first and provided detailed data on the fragmentation process of the debris cloud in both double base propellants. The measurements of fragment size distribution as a function of impact velocity have validated the damage model based on percolation theory.

- Small scale ignition test successfully observed ignition and growth of reactions in the debris cloud on impact with a transparent surface. The experiments have demonstrated the transition to XDT as the impact velocity increases and the gap distance decreases.

- The understanding gained of the experimental methodology will allow the development of a robust small scale test to determine the propensity of a propellant formulation to exhibit XDT behaviour together with the importance of rocket motor design parameters and materials to remove/mitigate this response.
9 Conclusions

Numerical Simulations

- Numerical simulations of the fragmentation process, given adequate resolution can reproduce the observed fragmentation behaviour.
- Limiting the rate of damage development in the propellant is an important controlling factor.
- The validation of the models in 3D has yet to be completed.
- The integration of the Porter-Gould damage model with CHARM has been successfully completed but remains to be rigorously validated. The need to fully implement the complete polymer composite model using a new numerical scheme has been identified as an important requirement for a fully predictive capability.
- The ability of CHARM to generate ignition in a high porosity representation of the debris cloud has been demonstrated. Validation against the ignition experiments remains to be completed.
9 Conclusions

Overall

- The research into materials science based material methods has demonstrated they can be used to predict the properties and behaviour of double base propellants.
- Small scale experiments are capable of understanding and characterising the fragmentation, ignition and burning behaviour of the debris cloud in XDT events.
- Numerical simulations, given sufficient resolution, can successfully reproduce the fragmentation process.
- The essential building blocks required to develop a predictive capability for XDT in rocket motors are in place to justify Phase II of the programme.