Institution:
University of Cambridge

Unit of Assessment:
UoA9

Title of case study:
High strain-rate material characterisation

1. Summary of the impact (indicative maximum 100 words)

Research undertaken in the University of Cambridge Department of Physics has provided benchmark data on, and fundamental physical insights into, the high strain-rate response of materials, including powdered reactive metal compositions. The data have been used widely by QinetiQ plc. to support numerical modelling and product development in important industrial and defence applications. One outcome has been the development of a reactive metal perforator for the oil industry which significantly outperforms conventional devices. These devices ‘perforate’ the region around a bore-hole, thereby substantially enhancing recovery, particularly in more difficult oil fields, and extending their economic viability. Over a million perforators have been deployed since their introduction in 2007.

2. Underpinning research (indicative maximum 500 words)

Since 1993, a large body of high strain rate research has been performed in the SMF Fracture & Shock Physics group (formerly the Physics and Chemistry of Solids group) at the Cavendish Laboratory, University of Cambridge under the leadership of Prof. John Field and later Dr. Bill Proud. Experimental techniques have been developed to study a wide range of materials including metallic systems, ceramics and polymers, as well as granular and energetic/reactive materials. A unique and important focus of the group’s research has been development of novel instrumentation, and simultaneous deployment of multiple diagnostics to maximise the information available from experiments. In relation to the impact described below, response of metals to high amplitude shock wave loading has been a particularly important area of research. For example, research in [1] provided an extended body of experimental data characterising the behaviour of tungsten. The investigation showed that the shear strength increases significantly with increasing stress, and this resolved a published disagreement in the literature. The data provided underlying physical understanding and measurements of parameters essential for developing numerical models of tungsten and tungsten alloy systems.

Development of accurate material models requires initial measurement of physical parameters, as described above, followed by validation experiments in more complex geometries, to confirm that the models conform to the experimentally observed behaviour. One such validation experiment is symmetric Taylor impact which, probes a range of different strain rates as well as both elastic and plastic responses in a single experiment. The research in [2] undertaken by the group in 1998-2000 described a series of such validation experiments for copper, a material widely used in high strain rate experiments and devices. The research included further development of the experimental technique, and provided new insights gained in the material response.

In addition to metals, the group has studied compaction of numerous granular / powdered materials, and the relationships between granular and consolidated materials. The research in [3] demonstrated the limitations of compaction models, and the need for comprehensive experimental characterisation. Research in [4] characterised the shock response of powdered aluminium compacts, and examined the applicability of various equations of state. This research represented the first measurement of spall strength of a porous ductile material, showing that the dynamic tensile strength of shock compacted porous aluminium is relatively small, and likely dependent on both the initial pore structure and strain rate. These are key concepts required in development of numerical material models for compressed powder compacts.

Leading on from the research strands described above and starting in 2009, the mechanical and reactive properties of pressed nickel-aluminium compacts have been studied over a variety of strain rates, including a study of the intermetallic reaction initiation and kinetics under shock loading. These experiments are described in [5] (performed in collaboration with QinetiQ plc).

In addition to Professor Field, the above research has been undertaken by a series of staff members within the research group:

Jeremy C.F. Millett, Research Associate 1995 to 1998
Neil K. Bourne, Royal Commission for the Exhibition of 1851; Research Fellow 1990 to 1994; Assistant Director of Research 1994 to 1998
John E. Field, Reader in Applied Physics 1990-1994; Professor in Applied Physics 1994-2003; Emeritus Professor of Applied Physics 2003 to present
William G. Proud, Research Associate 1995 to 2003; Head of Fracture and Shock Physics Group 2003 to 2009
Stephen M. Walley, Research Associate 1983 to present
Konstantinos Tsembelis, Research Associate 1998 to 2004
David M. Williamson, Research Associate 2006 to present
Christopher H. Braithwaite, Research Associate 2009 to present

3. References to the research (indicative maximum of six references)

[1] Millett J.C.F., Bourne N.K., Rosenberg Z. & Field J.E. "Shear strength measurements in a tungsten alloy during shock loading" J. Appl. Phys. 86, 6707 (1999); DOI: 10.1063/1.371748 *

[2] 2009 Forde L.C., Proud W.G. and Walley S.M. "Symmetrical Taylor impact studies of copper" Proc. R. Soc. A465 769-790, DOI: 10.1098/rspa.2008.0205 *

[3] 2005 Borg J.P., Chapman D.J., Tsembelis K., Proud W.G and Cogar J.R. "Dynamic compaction of porous silica powder", J. Appl. Phys. 98 073509, DOI: 10.1063/1.2064315 *

[4] 2009 Kraus R.G., Chapman D.J., Proud W.G. and Swift D.C. "Hugoniot and spall strength measurements of porous aluminium" J. Appl. Phys. 105 114914, DOI: 10.1063/1.3133237

[5] 2013 Church P., Claridge R,, Ottley P., Lewtas I., Harrison N., Gould P., Braithwaite C. and Williamson D. "Investigation of a nickel-aluminium reactive shaped charge liner" J. Appl. Mech. 80 031701, DOI: 10.1115/1.4023339.

*References which best reflect the quality of the underpinning research.

4. Details of the impact (indicative maximum 750 words)

Across industry, numerical simulation has become an increasingly important tool for understanding fast mechanical processes, due to both the high cost of performing full-scale experiments and the additional insights obtained through using these tools. Examples range from ballistic impact in a military environment to fragmentation of rock during mining operations. However, without experimental support to develop appropriate material models and validate output, such simulations are of limited value. In general, simulations can only be applied to complex systems with confidence if the high rate response of the underlying materials is well understood, characterised, and if adequate materials models can therefore be applied.

In terms of the impact described here, the specific area of interest is metallic systems. The body of underpinning research within the SMF Fracture & Shock Physics group has contributed to development and validation of a whole series of material models within industry, and led specifically to substantial model development and validation at QinetiQ plc. The details of exact models are proprietary, and many of the applications of such models are defence related. For many projects it is therefore difficult to provide detailed metrics relating to the impact, as it relates to confidential, commercially sensitive, or classified projects. However, one application in the public domain which demonstrates the impact of Cambridge material characterisation work is the development of a novel reactive metal perforator for the oil and gas industries.

The principle of the device is to use an explosively formed metal jet to perforate material around an oil/gas borehole, releasing oil & gas from the surrounding strata. Previously, QinetiQ plc developed perforator like devices using materials models validated against SMF Fracture & Shock Physics group data. The enabling research included basic understanding of the compaction and shock response of metallic systems, such as that described in [1]. For example, copper is widely used in explosively formed perforators, and the validation data described in [2] was made available to QinetiQ well before the publication date. The particular impact described here involved replacement of a standard metallic component with a reactive component formed from at least two species of compacted metal powders. Achieving this required a detailed understanding of the compaction and shock response of powdered materials [3,4].

The critical element of this new device was a reactive metal 'liner', formed from a mixture of compressed powdered nickel and aluminium. This enabled QinetiQ to develop novel equation of state (EOS) models for the composite material, making use of the underpinning high-rate material characterisation data provided by the SMF Fracture & Shock Physics group research. In addition to fundamental understanding [1-4], the SMF Fracture & Shock Physics group provided further specific data on the response of nickel-aluminium compacts. The data was in the form of a confidential technical report and data provided prior to the report, some of which has been reported in [5].

Using these models, it was possible to develop and test a novel reactive metal perforator rapidly, using a nickel-aluminium-titanium mixture. The device has been commercially produced since 2007 and has sold over one million units since then [6]. The oil and gas industries are substantial beneficiaries of the technology; the product enables more effective perforation of the rock strata around boreholes, substantially improving oil and gas recovery, particularly in more difficult oil fields, and thus extending their economic viability. The development of the project by QinetiQ plc, using underlying data provided by Cambridge, won the QinetiQ / DSTL John Benjamin Memorial Prize, 2012 [8]. Over a million devices have now been manufactured since 2007. Companies such as Shell (who were involved in commercialisation of the product, since the very first stages) have reported substantial increases in perforation charge performance using the new devices, which is measured through oil recovery (up to 30-40% increase) as summarised in article [9].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[6] Letter of support from QinetiQ Fellow, QinetiQ plc This supports the value of experimental insights, material characterisation data and validation experiments performed by the SMF Fracture and Shock Physics group, leading to the impact described above.

[7] Details of the novel reactive metal perforator are available from the Connex website, at www.perf.com/connex/ and a detailed description of the Connex product is available in the PDF brochure at http://www.perf.com/wp-content/themes/geodynamics/library/pdf/connex.pdf

[8] John Benjamin Memorial Prize 2012 application, written by QinetiQ. The document describes the development process and modelling for the Connex product. This is a commercially confidential document, but we have permission to submit it to the REF panel, if required.

[9] Online article, *"Perforating technology positioned to increase production"* from Offshore Magazine, http://www.offshore-mag.com/articles/print/volume-67/issue-10/drilling-completion/perforating-technology-positioned-to-increase-production.html