Institution:	**UNIVERSITY OF CAMBRIDGE**
Unit of Assessment:	**B13** Electrical and Electronic Engineering, **Metallurgy and Materials**
Title of case study:	**High-performance nanostructured-steel armour**

1. Summary of the impact

This Case Study builds on our sustained effort since 1981 to understand the nature of steel to an extent that enables the quantitative design of novel alloys and processes. In 1997 this led to the development of *Super Bainite* high-performance armour steel with an internal structure distinguished by an unprecedentedly high population density of interfaces. In 2011 this was licensed to *Tata Steel* who started manufacture at their Port Talbot, South Wales plant. The steel is destined for armoured vehicles. In a perforated design it has higher ballistic mass efficiency and is less expensive than conventional armour. The work at Port Talbot has re-established UK sovereign production of high-performance steel armour, after a gap of over 20 years.

2. Underpinning research

Slender crystals of ferritic iron can be grown in the solid state from austenitic iron, at a low temperature, by displacing the parent lattice into that of the product. Excess carbon then partitions into the austenite. The formation of this classical metallurgical structure, *bainite*, has for many decades been difficult to interpret, because the atoms involved have very limited mobility during the phase change. **Harry Bhadeshia** (on the academic staff of the Dept of Materials Science & Metallurgy (**DMSM**) at the University of Cambridge (**UCAM**) 1981 to date, and currently *Tata Steel Professor*) is noted for example as the inventor of the ultra-tough steel used for the rails in the Channel Tunnel. Supported by grants from a series of sponsors (Section 3), his systematic work has revealed the mechanisms and quantitatively characterized bainite formation.

Bhadeshia pioneered the concept that there is no fundamental lower limit to the temperature at which bainite can be produced, and predicted refinement of its structure and improvement of properties by heat treatment at lower temperature. Bhadeshia and FG Caballero (PDRA in DMSM, July 1997 to July 1999) worked with the Ministry of Defence (**MOD**) on designing a steel for gun-barrels, and discovered a bainitic steel that had very desirable ballistic and mechanical properties (strength 2500 MPa; toughness 40 MPa $m^{1/2}$). A patent was filed on this new composition and its manufacture [1], and a later paper [2] is highly cited.

The new steel required heat treatment at 200°C for 10 days, making it difficult to manufacture. Bhadeshia and C Garcia-Mateo (PDRA in DMSM, July 2000 to June 2003), funded by the EPSRC and MOD, confirmed the high strength obtainable at low temperature [3] and, crucially, showed how the bainite transformation could be accelerated [4]. Aiming at designing a steel for armour rather than gun-barrels, and using thermodynamic and kinetic modelling, alloys were identified and selected variants were made and tested. By the end, a *Super Bainite* steel with a transformation temperature of 200°C (a lowish temperature more associated with cooking pizza than with heat-treating steel!) that transformed in hours and not days, had been identified. The resulting material, with a strength in excess of 2500 MPa, has the highest density of interfaces ever reported from a phase change alone; the low-temperature treatment had created **the world's first bulk nanostructured metal**. In this *Super Bainite*, the ferritic crystals are only 20–40 nm thick.

From 2004, Bhadeshia worked with Dr Peter Brown from *DSTL*, as a result of which *Corus* (now *Tata Steel*) was contracted by *DSTL* to make tonnage quantities for large-scale evaluation (Fig. 1). In 2008, [text removed for publication]

. *Tata Steel*'s *Swinden Technology Centre* determined the cooling-rate window, slow enough to avoid cracking but fast enough to avoid the formation of deleterious carbide

Fig. 1. *Super Bainite* sheet under production†

phases. In 2008 a patent [5] was filed to protect the invention of a reduced-manganese nanostructured alloy that transforms rapidly, based on the work by Bhadeshia and Garcia-Mateo in collaboration with Brown, and further work has continued with Tata Steel [6].

The development of *Super Bainite* has led to a burgeoning new field of worldwide research [7]. At UCAM, further fundamental discoveries have been made (e.g. the first ever prediction and observation of non-cubic ferrite), and there are several new research projects on *Super Bainite* (its thermal stability, wear resistance, damage tolerance, etc.).

3. References to the research

1. J Mawella, FG Cabellero & HKDH Bhadeshia: 'Bainitic steel', World patent WO0111096
2*****. FG Caballero, HKDH Bhadeshia, KJA Mawella, DG Jones & P Brown: Very strong low-temperature bainite, *Materials Science and Technology* **18** (2002) 279; DOI: 10.1179/026708301225000725 [148 citations as of October 2013]
3*****. C Garcia-Mateo, FG Caballero & HKDH Bhadeshia: Development of hard bainite, *ISIJ International* **43** (2003) 1238; DOI: 10.2355/isijinternational.43.1238 [96 citations]
4*****. C Garcia-Mateo, FG Caballero & HKDH Bhadeshia: Acceleration of low-temperature bainite, *ISIJ International* **43** (2003) 1821; DOI: 10.2355/isijinternational.43.1821 [108 citations]
5. HKDH Bhadeshia, C Garcia-Mateo & P Brown: 'Bainite steel and methods of manufacture thereof', World patent WO/2010/013054, GB2462197, US 2011/0126946 A1
6. *Tata Steel* Patent Pending: 'Super Bainite steel and method for manufacturing it' (to be assigned to *MoD/Ploughshare Innovations*), application 10009375.6, 9th Sept. 2010.
7. HKDH Bhadeshia: The first bulk nanostructured metal, *Science and Technology of Advanced Materials* **14** (2013) 014202; DOI: 10.1088/1468-6996/14/1/014202

*****references best indicating the quality of the underpinning research.

Supporting research grants (all to Bhadeshia as PI)**:**

(1) DERA, July 1997 to July 1999, £81,224
(2) EPSRC (GR/N14620/01), July 2001 to June 2003, 'Very strong, low-temperature bainite', £233,955
(3) QinetiQ, July 2003 to January 2004, £25,000
(4) DSTL, August 2012 to August 2015, £420,575.

4. Details of the impact

Despite the vast amount of empirical data available, the underpinning fundamental research (Section 2) on atomic mechanisms was essential for the design of steel compositions and heat treatments to achieve the desired nanostructure without other undesirable reactions, as a function of many variables. The key invention enabled the heat-treatment time at the required low temperature to be brought within practical limits for large-scale manufacture, as incorporated in the patent documents. We now have the world's first bulk nanostructured metal, produced without deformation, rapid heat-treatments or expensive solutes, and which can be large in all three dimensions. The structure has the highest reported density of interfaces in a bulk material, responsible demonstrably for the properties achieved.

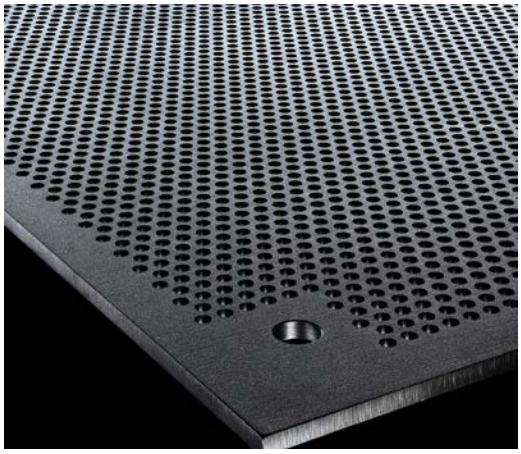

Fig. 2. Perforated *Super Bainite* armour†

DSTL found that when perforated (Fig. 2), the steel has a ballistic resistance exceeding that of well-established armour materials. Drilling and hole-punching prior to heat-treatment results in an ultra-hard perforated plate. The challenging technology by *Tata Steel* uses a novel technique related to CNC punch tooling to achieve punching with holes of diameter equal to or smaller than the gauge, while maintaining the flatness of the plate. The new

armour is fully protected by a patent granted to the Secretary of State for Defence in which UCAM has a share in royalties; supporting patent applications have been made worldwide. The patents are licensed to *Tata Steel (Europe)* who have developed the production technology to where [text removed for publication] . The product, *PAVISE™ Ultra High-Hardness Perforated Armour Steel*, is attracting approvals and initial orders from France, Germany, USA and India, in addition to the MOD (press release of 03/09/2013, Section 5). Production is based at Port Talbot. The steel as a perforated strike face is one of the best metallic armours ever produced. [text removed for publication]

. The initial focus is on UK armoured-vehicle programmes, extending to Indian programmes, mainland Europe and the significant US market. The perforated sheet is one of 7 forms intended for manufacture under *Tata Steel*'s licensing agreement with DSTL's technology-transfer partner *Ploughshare Innovations.*†

The Minister for Defence Equipment, Support and Technology, Mr Peter Luff, said [i]: "This cutting-edge UK invention and the manufacturing agreement mean that the UK now has its own onshore supply of high-performance armour steel. *Super Bainite* has both military and civilian applications, providing *Tata Steel* with important export opportunities. The application of new, battle-winning technologies is what gives our troops the edge. This demonstrates, once again, that investing in research and development, in partnership with industry, means that our troops can have the latest innovations in front line equipment." Production of the specialist armour-steel, and the successful development of the downstream processing technology by UCAM scientists working with *Tata Steel*, fulfils the UK MoD Defence Technology Strategy set out by Lord Drayson in 2006. UCAM research has enabled the Ministry of Defence to re-establish sovereign production of armour steel for the first time in more than two decades. It is applicable in composite armour systems enhanced with a perforated ultra-hard armour strike face, to resist potent ballistic threats.

The new armour has stimulated interest in high-carbon steel production within *Tata Steel* that had suffered serious technical problems in the past, as steel production capability was lost in the UK. The technology developed within *Tata Steel* for the continuous manufacture of *Super Bainite* at an integrated factory, is directly responsible for the reintroduction to the UK of the manufacture of high-carbon steels. There is demand in Europe for up to 400k tonnes per annum for items including springs, bearing cages and hand tools, where hard and thin sheets are required. The reintroduction also supported *Tata Steel* processes in Spain, [text removed for publication]

.

Towards expanding applications, new work has been funded by the MOD, revisiting that done at UCAM [FG Caballero, HKDH Bhadeshia, KJA Mawella, DG Jones & P Brown, *Mater Sci Technol* **17** (2001) 512]. *Tata Steel* now has teams looking at additional applications, e.g. in highly-profitable wear-resistant plates for the mining industries.

Main types of impact

Economic — Performance of existing business improved through new products & processes (*Tata Steel* production of armour steel for worldwide market); A new business sector or activity has been created (reintroduction of UK manufacture of high-carbon steels); Performance improved through highly skilled people taking up specialist roles that draw on their research (Many UCAM-trained people now working at *Tata Steel*).

Public policy & services — Risks to the security of nation states reduced (The MOD has access to high-performance cost-effective armour, improving safety and performance of security personnel; and UK sovereignty is protected by restoring indigenous manufacture).

Society — Research has contributed to community regeneration (inward investment into *Tata Steel* plant, safeguarding and creation of jobs in Port Talbot, S Wales).

5. Sources to corroborate the impact

[i] Quotation from Peter Luff available at:
(https://www.gov.uk/government/news/new-armour-steel-showcased-at-dsei)

Tata Steel
The financial details and production quantities outlined above from Tata Steel are commercially sensitive and should not be disseminated. They can, however, be verified by the Sector Development Manager, Defence Products Strategic Marketing.

Defence Science and Technology Laboratory (DSTL) (part of MOD)
A letter from the Deputy Chief Executive, DSTL verifying the claims made about the armour, and how this enhances defence strategy first outlined in 2006.

The Senior Principal Scientist, Physical Sciences Group, at DSTL directly involved in the UCAM collaboration can verify claims about the research history leading to *Super Bainite*.

†Figures 1 and 2, and information on licensing (p. 3) are from:
DSTL Annual Report and Accounts 2011/12
http://www.official-documents.gov.uk/document/hc1213/hc01/0123/0123.pdf

Press releases and other coverage (list not exhaustive)**:**

19th March 2008: DSTL press release "The story of the best armour steel ever made"
http://www.msm.cam.ac.uk/phase-trans/2008/wired.pdf

28th August 2008: DSTL press release "Supporting UK Defence Operations with innovative science and technology": https://www.dstl.gov.uk/downloads/28-08-08.pdf

3rd October 2008: Corus develops new low cost armour steel
http://www.tatasteeleurope.com/en/news/news/2008/2008_new_lowcost_armoured_steel

5th January 2009: BBC News "Holes give edge to new MoD armour"
http://news.bbc.co.uk/1/hi/sci/tech/7811567.stm

17th March 2010: DSTL press release: "Hole" new idea for armour
https://www.dstl.gov.uk/downloads/17March2010-4.pdf

14th Sept 2011: DSTL press release "UK invention brings sovereign capability for armoured steel"
https://www.dstl.gov.uk/downloads/20110914-Super_Bainite_Steel_PN_-_FINAL1.pdf

14th Sept 2011: *Wales Online* "Tata's Port Talbot steelworks earmarked to produce super-steel to be used on front line"
www.walesonline.co.uk/news/wales-news/2011/09/14/tata-s-port-talbot-steelworks-earmarked-to-produce-super-steel-to-be-used-on-front-line-91466-29421333/#ixzz1j49GXDB4

3rd Sept 2013: Tata press release "Tata Steel's lightweight armour steel can take a punch"
http://www.uk.tata.com/media/releases/inside.aspx?artid=Q0j5nZ6P4tc=