Preface

Adventures in the physical metallurgy of steels

H. K. D. H. Bhadeshia

Department of Materials Science and Metallurgy, University of Cambridge, Cambridge CB3 0FS, UK, email hkdb@cam.ac.uk.

The automotive industry is famous for introducing concept-cars that set the vision for the future. The Cambridge Adventures, held on 23–25 July 2013, had the goal of resetting the meaning of conferences, and to provide a template for meetings of the future. Attendance at 'Adventures in the physical metallurgy of steels' (APMS) was therefore limited to 100 people on the basis of risk, novelty and excitement in their research. There were no invited lectures. The number of presentations was limited to 25, without parallel sessions. There was no theme to address other than the broad one defined by the title, so each talk was a breath of fresh air. There were no registration fees, the meeting was broadcast live on the internet for those not attending to watch free-of-charge and to participate live in the discussions irrespective of geographical location. All presentations were professionally recorded and are available to view on YouTube. And now, here are the proceedings, made freely accessible for a number of years.

This special issue of *MST* deals with the publication phase of the meeting, with each paper having been independently reviewed according to the standard *MST* procedures.

An intriguing subject is that of the electrical modification of steels, by using short but intense electrical pulses to stimulate changes in the microscopic structure. The Russians have a reputation in metallurgy of doing things that are outside of the box; the earliest report on the effect of electrical pulses seems to be by Troitskii from the Russian Academy of Sciences,[1] who investigated the influence of the pulses on the plasticity of zinc and cadmium crystals*. The field has since then been of peripheral interest with diverse materials, mostly ferrous but also other systems,[3,4] being subjected to this shock treatment. Rongshan Qin gave a wonderful exposition of the subject at APMS, including the latest examples from his research. My impression is that there is promise in taking the concept towards application, but that although theoretical interpretations exist, they have yet to be applied in vengeance to interpret the experimental data. One contribution from Russia dealt with the introduction of large molecular weight carbon into steels using mechanical alloying; the work was interesting but requires high-resolution characterisation to discover whether the carbon simply dissolves in the iron or exists as large obstacles within the structure.

One of the most difficult challenges in steels is the welding of very high carbon alloys ($\sim$1 wt-%). Such alloys have become technologically important but as is well known,[5] the carbon equivalent becomes unacceptable for welding purposes. Inspiring work done at the Harbin Institute of Technology is helping to overcome the difficulties by using a method that does not allow the heat-affected zone of an arc weld to transform into martensite. Friction stir welding may be an alternative but as DebRoy pointed out, we are at the early stages of understanding the development of structure on a quantitative basis, and although there are issues regarding tool life,[6] they may not be limiting depending on the cost and need for the manufacture of particular components. The pernicious problem of type IV cracking[7] in creep-resistant steels appears to have been solved by Abe and co-workers using the interaction of boron with vacancies to impart long term stability to the precipitates present in the microstructure. In contrast, Wu and co-workers described how to control the nature of carbides using external fields.

Rapid processing has clear advantages when it comes to steel manufacture. A subject that is arousing passions and intense discussion is the invention of the so-called flash processing. In this, the cementite-containing steel is heated so rapidly, that the carbon resulting from the dissolution of cementite in austenite remains localised, so that the average concentration in most of the austenite is small; as a result, the austenite transforms rapidly into bainite on cooling: time intervals of some 80 ms are mentioned.[8] Two fascinating new papers were presented, one attempting to validate the hypothesis by making predictions in the best traditions of science, and the other describing how the process has now been scaled up and instrumented. In contrast, a variety of papers were presented on slow bainite, the invention of which was first reported some twelve years ago in this journal.[9] The excitement centred around two aspects – major commercialisation by several industries, and the discovery by Caballero and co-workers of the high concentrations of carbon that remain in solid

*A recent report[2] seems to have demonstrated an inverse effect, that there is an electrical current spike associated with deformation.

© 2014 Institute of Materials, Minerals and Mining
Published by Maney on behalf of the Institute
DOI 10.1179/0267083614Z.0000000724

solution inside the bainitic ferrite, carbon that is reluctant to partition. There may here be a link with the quench and portioning process described by Speer, which now even has the potential of changing stainless steels.[10] We are hoping that Speer will soon publish separately a critical assessment of the whole subject. A unique paper on secondary-hardened, low-carbon bainite by Yang demonstrated the potential for further developments in the ubiquitous automotive range of steels.

The word 'architectured' applied to a number of presentations, whether that involves creating a layered structure of stainless steel and magnesium, metal-rich particles added deliberately to high-speed steel to stimulate nucleation (inoculation with non-metallic particles is common in steels[11]) or the amazing characterisation by Capdevila and co-workers of yttria-rich particles in mechanically alloyed iron. A different kind of mechanical alloying, in which particles of copper present in iron, dissolve during deformation, was presented by Tsuchiyama; the mechanism here is to cut the particle to a size that is not sustainable due to the surface-to-volume ratio. The production of weird compounds by mechanosynthesis, another form of architecturing, was described by Miani. A particular goal for the future should be to produce isotropic polycrystalline steel; variations in properties relative to the major processing direction causes huge difficulties in pipeline design[12–16] and bearing steels.[17,18] In the latter case, it is the size, shape and distribution of inclusions that matters and Ölund demonstrated how particles can be modified to control these characteristics. Kundu demonstrated how external influences can cause changes in microscopic texture. As a general point, there has been huge activity on the development of texture but none explicitly on its elimination to enhance isotropy and thereby open up new engineering designs based on steels. Perhaps inspiration can be obtained from the nice presentation by Anand on the architecting of microstructures.

First principles calculations are now routine in metallurgy; Igor Abrikosov explained his remarkable breakthrough that led to an elegant interpretation of the magnetic properties of iron, that are so dominant in determining its characteristics. For example, in the absence of ferromagnetism, iron would be hexagonal with all the difficulties that go with that – the non-magnetic iron analogues, ruthenium and osmium, are indeed hexagonal. Tony Paxton emphasised the quantum nature of the hydrogen atom in iron, and Dong Woo Suh presented a new interpretation of the reluctance of carbon to partition from supersaturated ferrite. I once was critical of the way the field was progressing,[19] with an overemphasis on covering the length scales for the sake of doing so, and with exaggerated claims about the power of simulations. I firmly believe that it is the combination of metallurgists and *ab initio* thinkers that is responsible for the renaissance that we now see. The strength of the method over history has been in addressing physical properties such as optics,[20] but it has now been applied with significant success, to gain insight into the macroscopic properties of structural materials and to actually design new steels.[21] The outcomes from first principles calculations form the basis for potentials that go into simulations involving large numbers of atoms, and a particular application of this to void formation and ductility reached the simple conclusion that in a single crystal, voids occur at tangled dislocations but in polycrystalline systems at grain boundaries. In a sense this work also highlights the difficulties because the number of atoms involved is still miniscule ($<10^5$) so that the myriad of defects and particles in real materials cannot frankly be addressed.

Alloys of austenitic iron containing large concentrations of manganese (typically 15–20 wt-%) are now common in research and are commercially available;[22–24] they rely on twinning-induced plasticity (TWIP) to achieve the work hardening that delays plastic instabilities. While some applications exist, the component-manufacturing industry is still absorbing knowledge on how to apply these materials that have extraordinary combinations of strength and ductility. One possibility, described by Dye, is as a blast-resistant steel that, for ease of replacement in a conflict scenario, should be joined mechanically rather than welded. The nano-indentation method proves particularly useful in the study of hydrogen in TWIP steels, because the hydrogen can only penetrate a layer extending about 100 μm below the surface;[25] the sudden displacement discontinuity (pop-in) that features in the load–extension curves is a useful sources of information in that context. The role of solutes added to combat hydrogen in TWIP steel is critically assessed in a forthcoming article.[26] Some of these high-manganese steels contain substantial quantities of silicon and aluminium, which contribute to a reduction in density from about 7·8 to 7·3 g cm^{-3}. Precipitation-hardened varieties were discussed by Gutierrez-Urrutia. Yi argued for a low-density, low-alloy bearing steel that seems to have remarkable hardness, coupled with the ability to counter carbide networks and to avoid retained austenite.

Microstructural characterisation is of course a part of the definition of materials science in general[27] and the relationship between structure and properties distinguishes the subject from the pure sciences or engineering. It would therefore be wonderful to be able to measure microstructure as it evolves during the processing of steels.[28] It is heartening therefore, to see that Davies and others are working on precisely this objective. There remain difficulties, but that exactly is what this conference was about. I once again would like to thank the sponsors who made this once-in-a-

lifetime adventure possible: CBMM, POSCO, SKF and Tata Steel. The sponsors possibly may not appreciate the enormity of their help, but this adventure has created science by discussion, and the resulting knowledge continues to be freely disseminated to a huge audience. We are grateful, more than grateful. With the publication of these proceedings, the organisers' tasks come to an end – although all the information remains live for anyone to access. I thank particularly all the staff responsible for the production of *Materials Science and Technology* for their constructive engagement in this process. The participants – what would we have done without them? The support team at Cambridge – they know how much I have appreciated their help and vision.

References

1. O. A. Troitskii: 'Electromechanical effect in metals', *JETP Lett.* (English version), 1969, **10**, 11–14.
2. R. Nowak, D. Chrobak, S. Nagao, D. Vodnik and M. Berg: 'Mystery of current spike: nanoscale plasticity revisited', *Mater. Sci. Technol.*, 2012, **28**, 1202–1206.
3. H. Conrad, N. Karam and S. Mannan: 'Effect of electric current pulses on the recrystallization of copper', *Scr. Metall.*, 1983, **17**, 411–416.
4. W. H. Cao, J. L. Zhang and C. H. Shek: 'Effects of electropulsing treatment on mechanical properties in Ti rich TiNi shape memory alloy', *Mater. Sci. Technol.*, 2013, **29**, 1135–1138.
5. N. Yurioka and H. Suzuki: 'Hydrogen assisted cracking in C–Mn and low alloy steel weldments', *Int. Mater. Rev.*, 1990, **35**, 217–249.
6. R. Rai, A. De, H. K. D. H. Bhadeshia and T. DebRoy: 'Friction stir welding tools', *Sci. Technol. Weld. Joining*, 2011, **16**, 325–342.
7. J. A. Francis, W. Mazur and H. K. D. H. Bhadeshia: 'Type IV cracking in ferritic power plant steels', *Mater. Sci. Technol.*, 2006, **22**, 1387–1395.
8. T. Lolla, G. Cola, B. Narayanan, B. Alexandrov and S. S. Babu: 'Development of rapid heating and cooling (flash processing) process to produce advanced high strength steel microstructures', *Mater. Sci. Technol.*, 2011, **27**, 863–875.
9. F. G. Caballero, C. Capdevila and C. G. de Andrés: 'Evaluation and review of simultaneous transformation model in high strength low alloy steels', *Mater. Sci. Technol.*, 2002, **18**, 534–540.
10. J. Mola and B. C. De Cooman: 'Quenching and partitioning processing of martensitic stainless steels', *Metall. Mater. Trans. A*, 2012, **65**, 834–837.
11. T. Koseki and G. Thewlis: 'Inclusions in welds', *Mater. Sci. Technol.*, 2005, **21**, 867–879.
12. A. A. Kichkina, M. Y. Matrosov, L. I. Efron, M. B. Klyukvin and A. V. Golovanov: 'Effect of structural anisotropy of ferrite-bainite pipe steel on mechanical properties in tensile and impact bending tests', *Metallurgist*, 2011, **54**, 808–816.
13. J. H. Bae, S. H. Choi and K. B. Kang: 'Effect of thermomechanical processing parameters upon texture development and yield strength anisotropy in high strength linepipe steels', *Mater. Sci. Forum*, 2002, **408–412**, 1179–1184.
14. R. Petrov, O. L. Garcia, N. S. Mourino, L. Kestens, J. H. Bae and K. B. Kang: 'Microstructure–texture related toughness anisotropy of API–X80 pipeline steel characterised by 3D–EBSD technique', *Mater. Sci. Forum*, 2007, **558–559**, 1429–1434.
15. M. S. Joo, D.-W. Suh, J. H. Bae, N. Sanchez Moriño, R. Petrov, L. A. I. Kestens and H. K. D. H. Bhadeshia: 'Experiments to separate the effect of texture on anisotropy of pipeline steel', *Mater. Sci. Eng. A*, 2012, **556**, 601–606.
16. M. S. Joo, D.-W. Suh, J.-H. Bae and H. K. D. H. Bhadeshia: 'Toughness anisotropy in X70 and X80 linepipe steels', *Mater. Sci. Technol.*, 2014, **30**, 439–440.
17. P. Walker: 'Improving the reliability of highly loaded rolling bearings: the effect of up-stream processing on inclusions', *Mater. Sci. Technol.*, 2014, **30**, 385–410.
18. H. K. D. H. Bhadeshia: 'Steels for bearings', *Prog. Mater.Sci.*, 2012, **57**, 268–435.
19. H. K. D. H. Bhadeshia: 'Mathematical models in materials science', *Mater. Sci. Technol.*, 2008, **24**, 128–135.
20. B. Koack, Y. O. Ciftci, K. Colakoglu, E. Deligoz and A. Tartar: 'Pressure depended elastic, vibration and optical properties of NbIrSn from first principles calculations', *Mater. Sci. Technol.*, 2013, **29**, 925–930.
21. G. B. Olson: 'Genomic materials design: the ferrous frontier', *Acta Mater.*, 2013, **61**, 771–781.
22. O. Grässel, L. Kruger, G. Frommeyer and L. W. Meyer: 'High strength Fe–Mn–(Al,Si) TRIP/TWIP steels: development – properties – application', *Int. J. Plasticity*, 2000, **16**, 1391–1409.
23. G. Frommeyer, U. Brüx and P. Neumann: 'Supra-ductile and high-strength manganese-TRIP/TWIP steels for high energy absorption purposes', *ISIJ Int.*, 2003, **43**, 438–446.
24. B. C. De Cooman, O. Kwon and K. G. Chin: 'State-of-the-knowledge on TWIP steel', *Mater. Sci. Technol.*, 2012, **28**, 513–527.
25. D. K. Han, Y. Kim, H. N. Han, H. K. D. H. Bhadeshia and D. W. Suh: 'Hydrogen and aluminium in high-manganese twinning-induced plasticity steel', *Scr. Mater.*, 2014, http://dx.doi.org/10·1016/j.scriptamat.2014·01·039.
26. D. W. Suh: 'Critical assessment 2: Hydrogen-induced fracture in austenitic, high-manganese TWIP steel', *Mater. Sci. Technol.*, 2014, http://dx.doi.org/10·1179/1743284714Y.0000000566.
27. M. Kranzberg and C. S. Smith: 'Materials in history and society', *Mater. Sci. Eng.*, 1979, **37**, 1–39.
28. J. F. Bussiere: 'On-line measurement of the microstructure and mechanical properties of steel', *Mater. Eval.*, 1986, **44**, 560–567.