BIOGRAPHICAL MEMOIRS

Edwin Smith. 28 July 1931 — 4 July 2010

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originally published online April 26, 2017

Supplementary data

"Data Supplement"
http://rsbm.royalsocietypublishing.org/content/suppl/2017/05/17/rsbm.2017.0008.DC1

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Elected FRS 1996

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Ted Smith is best known for his contributions to the analysis of continuous dislocations in deformed crystals and the application of this to understanding the conditions leading to plastic flow and fracture in metals. He applied his knowledge to a range of practical problems, particularly ones concerned with the structural integrity of key components in the nuclear power generation industry. His career spanned both industry and academia, including 20 years as Professor of Metallurgy at the University of Manchester, during which time he helped oversee the joint operation of the Departments of Metallurgy at both the University and UMIST and served at senior levels in the University administration. His research was frequently motivated by interactions with industry in consultancy work. He published over 500 papers, the great majority of which were of his sole authorship.

EARLY YEARS AND EDUCATION

Ted Smith was born on 28 July 1931 in the mining village of Staveley in Derbyshire, the son of Albert Edwin and Sarah Ann Smith. His father was initially a coal miner but later became a full-time mine rescue worker, being involved with rescue activities at the Markham Disaster (1938) and the Cresswell Disaster (1951). In his later career, Albert Smith was safety officer at High Moor and Ramcroft Collieries.

After early schooling in Ilkeston and Chesterfield, Ted was awarded a special place at Chesterfield Grammar School in 1941, where he stayed until 1949, obtaining a state
scholarship in his final year. He became a prefect and house captain in his last year; he was also confirmed and became a server at Chesterfield Parish Church. It gave him special pleasure to be asked to become President of the School Old Boys Society (the old Cestrefeldians) in 1997.

Ted’s strength at school was in mathematics and, although not enthusiastic about going to university, he was persuaded by his father and the school to join the honours course in mathematics at Nottingham University in October 1949. He admitted that he did not work very hard in his first year but did very well in the end-of-year examinations. Seeing the potential of what he could do if he worked hard, his whole attitude to his future career changed; as a result, he obtained a first class degree, specializing in hydrodynamics and statistics. He was then awarded a Department of Scientific and Industrial Research scholarship, which allowed him to study for a PhD. However, his head of department at Nottingham felt that Ted was not suited for applied mathematics research at Nottingham and recommended that he should seek opportunities in a more applied discipline, ‘where research would be easier’.

**EARLY RESEARCH AND PHD**

As a result of this advice, Ted became a postgraduate student in the Department of Metallurgy at Sheffield University from October 1952 to September 1955, living at home in Chesterfield and travelling by train each day to Sheffield. Because of the change in discipline from mathematics to metallurgy, he spent the first six months attending lectures, both undergraduate and postgraduate, and reading as much as possible about metallurgy. He then began research for a PhD under the supervision of B. A. Bilby (FRS 1977). His work was both theoretical and experimental, with encouragement on the experimental side from R. W. Honeycombe (FRS 1981). The theoretical work was concerned with the development of the theory of continuous dislocations in deformed crystals, a topic in which Ted was to become a leading expert and make significant contributions in the future. An important contribution was the posing and solving of the problem of following a constant crystallographic direction through the rotated lattice. He analysed a special case of the general theory of continuous dislocation distributions to predict the shapes of glide planes in bent zinc crystals (2)*. The experimental work he carried out involved studies of the effects of copper plating on the torsional deformation behaviour of single crystals of zinc; the experimental results agreed with the predictions from the theoretical analysis, providing confirmation of the validity of the theory.

Ted regarded the time he was at Sheffield as very exciting, as he was involved in the rapid development worldwide of understanding the behaviour of dislocations and their influence on plastic deformation and fracture of metals and alloys (1, 3). This built on conceptual contributions on dislocation theory that were being made by A. H. Cottrell (FRS 1955) and B. A. Bilby (Cottrell and Bilby 1949); at the same time, P. B. Hirsch (FRS 1963) observed dislocations in thin metallic films using the electron microscope. Ted wrote up his thesis after he left Sheffield in September 1955 and was awarded his PhD in 1957 for the topic ‘Continuous distributions of dislocations in deformed metals’.

* Numbers in this form refer to the bibliography at the end of the text.
Early career: industry

Associated Electrical Industries Research Laboratory, Aldermaston

Ted joined the Physical Metallurgy Section of AEI Research Laboratories, Aldermaston, in October 1955, where the director was T. E. Allibone FRS. He became head of the Deformation Studies sub-section in 1958. During his six-year stay at Aldermaston, Ted worked on a wide range of experimental research topics, including hydrogen embrittlement of titanium alloys, fracture of magnesium alloys as used for Magnox nuclear fuel elements, point defect mobility in titanium and zirconium, and plastic deformation, in particular the mechanical twinning of rhenium, zirconium and beryllium. He was somewhat disappointed with his time at Aldermaston, feeling that the work was not sufficiently focused and hence unproductive in terms of research success. He did, however, enjoy the social life and it was here that he met and married his wife, Pat.

Central Electricity Generating Board Research Laboratories, Leatherhead

In July 1961, Ted joined CEGB Research Laboratories (CERL) at Leatherhead to set up and lead the Metallurgical Engineering section. The original intention was that the section would concentrate on high temperature and creep properties of steels used in power generation plants. However, Ted built up the section by recruiting 12 research workers, all with PhD qualifications (including one of the present writers, JFK (FRS 1990)); figure 1 shows a contemporary photograph of the section. Once the section’s research programme was established, he conducted his own personal research on related theoretical aspects. Thus, he continued work on dislocation models of plastic flow and fracture at cracks and notches.

At CERL, Ted was an excellent section head. Not only did he lead by example in terms of research output and publications, but he also took a keen interest in the individual or projects being carried out by his research team. He provided informed criticism on the current research and was fully involved in planning new lines of research. His name appeared as co-author only on papers to which he had made a substantial contribution in terms of mathematical analysis or modelling. JFK writes: ‘I benefited particularly from his close attention to detail. He insisted that every step in an argument should be fully supported. This often led to further experimental confirmation and meant that any statements in published papers were fully supported.’

During this period, Ted was the chairman of the industry working party for collaborative research on brittle fracture and fatigue problems in generating equipment set up by CEGB. He was also a member of the Admiralty Advisory Committee on Structural Steels. He was awarded a special merit promotion in 1966 in recognition of his personal research achievements.

From March to April 1968, Ted was given special leave to work at Battelle Memorial Institute, Columbus, Ohio, collaborating on topics of common interest to both organizations. His time there opened his eyes to opportunities for international collaboration which he developed further later in his career. He did not seek a job in the USA, but as soon he returned from there, he was offered the post of Professor of Metallurgy at Manchester University.

Academic career: teaching and research

When Ted moved to Manchester in October 1968 there were separate Departments of Metallurgy in the University of Manchester and at UMIST (the University of Manchester
Institute of Science and Technology). Both Ted and Ken Entwistle, then head of the UMIST department, were keen to merge the two departments and they persuaded the two institutions (which, although academically linked through different faculties of the University, were financially and administratively separate) that it made sense to bring the departments together in a new building; this eventually happened in 1975. Although the two departments remained legally separate until the merger of UMIST and the University in 2004, they were managed and operated as a single unit from 1975 onwards. Prior to the departments coming together, they were both rated as average in research exercise assessments but the research standing then increased progressively – Ted’s personal research contribution being a significant factor – until in the 2002 research assessment exercise they were rated as 5*, the highest possible grading. Ted was administratively responsible for the University part of the department from 1970 until 1988, when he took early retirement.

Ted enjoyed teaching undergraduates and at various times he taught courses on mechanical properties, diffusion, fracture mechanics and nuclear materials to metallurgy students, as well as giving general materials courses to students from engineering departments.

Ted had originally intended to follow a similar line with his research to the one he had adopted at CEGB: that is, to build an experimental research group and then carry out theoretical research himself. However, his plans changed as he became more involved with industrial problems and he chose to focus his personal research on investigating theoretical problems inspired by industrial contacts.

Dislocation models, plastic flow and fracture

A feature of many of the models developed in Ted’s work was the representation of stress relaxation at crack tips and notches by continuous distributions of dislocation arrays, following
work at Sheffield with Bilby, Cottrell and Swinden (4). He applied these methods while at the
CEGB Research Laboratories in a series of papers published in the *Proceedings of the Royal
Society* (5–7), leading to a paper on the assessment of the effect of component geometry and
notch shape on the failure of engineering components, using the crack opening displacement
criterion for the initiation of fracture (10).

Ted always considered that his most valuable work was the series of papers he wrote on
wedge cracks, which led to papers on cleavage crack nucleation (8) and particularly the effect
of second-phase carbide particles on the brittle fracture of ferritic steels (9). In this he was able
to quantify the effect of microstructure on the brittle fracture of steels, with a key feature of
the work being the recognition that the critical event in the failure process was the growth of
a carbide-size crack into the surrounding ferrite matrix.

An important extension of these models showed how key parts of a dislocation array
could be treated as discrete, the remainder of the array being a continuous distribution of
dislocations. This approach was used to examine details of the crack nucleation process and
to explore the theory of work-hardening (11).

Ted studied the effect of discreteness of the atomic structure on cleavage crack extension
using a simple one-dimensional model, giving particular attention to the effect of the inter-
atomic force law on the lattice trapping effect (12).

Building on his work from the 1960s, Ted was concerned to extend classical fracture
mechanics treatments of cracks to the behaviour of notches, which, although causing stress
concentration regions, could be expected to be less severe than cracks. His strategy was
to parallel, as far as possible, the process zone representation of the non-linear processes
that are associated with fracture. The characterizing parameter is the elastic peak notch-
tip stress, with fracture initiating when the peak stress attains a critical value, this being
equivalent to the attainment of a critical displacement where the process zone meets the notch
surface. The critical elastic peak notch-tip stress is related to the notch-tip root radius and
material parameters. A straightforward procedure, referred to as ‘the two extremes procedure’,
bloods the small and large process zone solutions to provide a simple expression for the
critical elastic peak stress (20). An overview paper (joint with D. Scarth) entitled ‘Extending
fracture mechanics for cracks to the behaviour of notches’ received the American Society of
Mechanical Engineers Outstanding Paper Award for 2001 (19).

Ted’s work in these general areas of application of dislocation models to cleavage fracture
problems has found wide application to both microscopic and macroscopic fracture problems.
All of his work was carried out by obtaining closed solutions by mathematical analysis without
the use of computers and without the use of finite element methods, but his pioneering work
often provided a foundation for others to explore further using computer-based methods.

**Failure mechanisms in nuclear materials**

During the whole of his career, Ted was particularly concerned with safety and reliability
issues associated with the nuclear industries in the UK, USA and Canada, and much of his
research was motivated by these issues. In a series of papers with colleagues from the Electric
Power Research Institute (EPRI), he studied the problem of iodine stress corrosion cracking
in zirconium alloy fuel cladding material, with stresses induced by the interaction between the
uranium dioxide fuel pellets and the cladding. Most importantly, this work was able to explain
the role of the internal friction coefficient and the effect of interlayers in reducing friction
and so preventing failure (13).
Ted developed a methodology for predicting the rate of growth of a stress corrosion crack at the high-stress levels often found in service, based on a crack tip opening angle (CTOA) approach (14). At low-stress levels, the methodology reduced to being equivalent to a linear elastic fracture mechanics (LEFM) approach, but the LEFM methods under-predicted growth rates at high-stress levels, whereas the CTOA approach gave better predictions.

He also devoted much effort to the problem of the behaviour of stainless steel reactor pipework. For normal operational conditions in reactors, he provided valuable underpinning support for the net section stress criterion for stainless steel piping failure (18). He also showed that piping systems have a large safety margin against pipe severance, for a wide range of pipe system and crack geometries under accident loading conditions, where inertial and displacement loadings are of prime importance (16). He devoted particular attention to the effects of restraint conditions on the response of stainless steel piping systems when subject to accidental loading. He received the American Society of Mechanical Engineering Outstanding Paper Award for 2002 for his paper on the effect of restraint non-linearity on instability of a circumferential through-wall crack in a piping system (21).

Ted carried out a number of studies investigating potential crack arrest in the thick-walled ferritic steel pressure vessel of a pressurized water reactor (PWR). He showed that the simple pseudo-static crack arrest procedure is conservative (17) and he also quantified the effects of the austenitic steel cladding at the vessel inner surface (15).

Delayed hydride cracking in zirconium alloys

Ted became involved with the Canadian nuclear industry from the early 1980s, initially reviewing the Canadian fracture mechanics programme for ensuring the structural integrity and safety of the CANDU nuclear reactor Zr-Nb pressure tubes. From about 1990, the country’s nuclear industry recognized that they needed a new methodology to evaluate the significance of cracks in these pressure tubes. The problem of delayed hydride cracking in zirconium–niobium alloys is of particular concern regarding potential deterioration of pressure tubes in this type of commercial nuclear reactor system. The basic mechanism is that there can be a diffusion of hydrogen atoms to stress concentration regions, such as blunt notches, and this can lead to precipitation of local hydride regions which subsequently develop cracks. Ted collaborated with research teams in the nuclear industry in Canada to work on this problem and was particularly proud of his work in this field. He helped to develop a flaw evaluation method for assessing the significance of such regions to the integrity of the pressure tubes in service. The method was based on representing the stress relaxation due to the formation of the hydride region by a process zone analogous to the relaxed zone used to describe plastic relaxation at cracks and notches in his earlier work. This method formed the basis for a Canadian standard on ‘In-service evaluation of zirconium alloy pressure tubes in CANDU reactors’. Ted formed many friendships through his work on these problems and he earned the highest respect of many individuals in the Canadian nuclear industry.

Elastic softening materials

Ted devoted considerable effort to modelling the toughness and crack growth resistance for elastic softening and ligament toughening materials such as concrete, rocks and other materials with a ceramic base, where the crack is restrained by ligaments behind the tip. He quantified the effects of geometrical parameters and of the material softening law on the fracture behaviour of these types of material. He also developed expressions for the cohesive
zone size and the critical crack extension stress for a crack tip with a class of non-linear stress-displacement laws in the cohesive zone.

**ACADEMIC CAREER: ADMINISTRATION**

For a two-year period from October 1983 to September 1985 Ted was appointed as Dean of the Faculty of Science in the University of Manchester, which was the largest faculty in the University. As such, he was responsible for the overall academic and financial administration of a wide range of disciplines, including maths, science and those engineering departments in the faculty (there were parallel departments in these areas in UMIST as the Faculty of Technology, which had its own dean). This was a period of retrenchment in universities after the government introduced full-cost fees for overseas students, and Ted had the difficult job of trying to promote a mood of optimism in the faculty while at the same time maintaining his departmental and personal research activities.

As a result of his success in carrying out the responsibilities of dean, Ted was persuaded by the Vice-Chancellor (M. H. Richmond FRS) to take on the responsibility of a pro-vice chancellor of the University, a role which he carried out from October 1985 to September 1988, when he took early retirement from full-time employment at the University. As pro-vice chancellor, Ted was a member of many key committees in the university structure, and chaired a number of them. He also acted as a key link between the University and UMIST and he still maintained his activities within his own department. As well as continuing his own research, he willingly acted as an independent internal examiner for several PhD students who had been supervised by one of the present writers (FMB (FRS 1993)).

The portrait of Ted Smith (figure 2) is one of a series of senior academics at the University of Manchester/UMIST painted by Stephen Ashurst. A tribute to Ted recorded at the Senate of the University of Manchester on his formal retirement in 1988 included the following statement:

> His skill is to distil the essence of a problem in a form that might be condensed on to the back of an envelope. His clear thinking and critical mind have produced important advances in the understanding of the integrity of nuclear fuel rods, of pressure vessels and piping and of steam generators . . . . He is single minded to a fault and desperate to excel in anything to which he allocates his gifts, be it squash, academic work or predicting the winner of the U.S. Open Golf Championship.

**EXTERNAL ACTIVITIES AND CONSULTANCY WORK**

Both before and after his early retirement from his post in Manchester, Ted’s approach was to interact closely with industry and much of his theoretical research was motivated by these industrial contacts. Among these were the following:

(a) AWRE Aldermaston on Beryllium project (1969–72).
(b) Pratt and Whitney, USA on mechanical properties of high strength alloys (1973–75).
(c) Failure Analysis Associates, USA, with EPRI on nuclear fuel rod performance (1975–78).
Figure 2. Portrait of Ted Smith by Stephen Ashurst in the Manchester Materials Science Centre. Photograph of portrait by Stephen Ashurst provided by Professor A. H. Sherry. (Online version in colour.)

(d) EPRI, USA, on a wide range of projects concerned with use of materials in nuclear reactors (1978–93, often spending periods of 3–4 months a year at Palo Alto with EPRI staff).
(f) CEGB on piping issues in PWRs (1987).
(g) UK Atomic Energy Authority on pressure tube and structural integrity issues in the Steam Generating Heavy Water Reactor (SGHWR) (1983–93).
(h) HM Nuclear Installations Inspectorate on pressurized zirconium tubes (1988) and pressure vessel crack arrest issues (1992–94).

Although he was somewhat sceptical of the value of independent advisory committees, Ted was a member of the Admiralty Advisory Committee on Structural Steels from 1966 to 1968
Edwin Smith

and of the Nuclear Safety Advisory Committee Study Group on Integrity of Pressure Circuits in PWR and SGHWR Reactors from 1974 to 1983. In 2003 he was persuaded to join the Nuclear Industries Technical Advisory Committee on Structural Integrity (TAGSI). He made a number of valuable contributions to the advice given by this committee to the nuclear industry, particularly on the issues of estimation of fracture toughness in parent steels and welds for reactor pressure vessels for PWRs from small-scale tests, fracture from stress concentrations, and the interaction effects between adjacent cracks, before retiring in 2007.

At various times Ted served on the Armourers and Braziers’ Committee and the Mullard Committee of the Royal Society. He was also Chairman of the Research Grants Board (Engineering Sciences and Materials Science) and of the International Conference Grants and Short Visits Committee.

PERSONAL LIFE AND LEISURE INTERESTS

Ted was a keen sportsman, both as a follower and as a participant. He was a firm believer that participation in competitive sport was a great help in other walks of life and he was fiercely competitive in his sporting activities himself. He took part in a wide range of sporting activities at Chesterfield Grammar School, including cricket, football, rugby, tennis, fives, table tennis and boxing, representing the school at cricket and football. At cricket, he was an opening batsman and occasional wicket keeper. In his last year at school he was selected to play for the Derbyshire under-21 team against Yorkshire at Sheffield, top scoring for his side before being caught out by Ray Illingworth (England cricket captain in later years).

Ted developed an interest in mountain walking and rock climbing while at university, and this led on to a desire to run a marathon, which he first did in April 1955. Between 1955 and 1959 he ran 14 marathons, with a best time of 2 hours 47 minutes. When he moved to take up his post at Leatherhead, he returned to playing cricket and football, captaining the CEGB Laboratory cricket team for two years. He also played for Horsham and scored 112 not out in a match at West Hove, but was out first ball in the corresponding match the next season, much to everyone’s amusement, including his own. The extensive participation in sport caused damage to his knee but his nervousness of medical treatment meant that he did not have this fixed, leaving him with a permanent limp. In his final years he became virtually housebound though still mentally very active.

Ted met his future wife, Pat, when he was working at AEI Laboratories, Aldermaston, where she was secretary to the head of the physical metallurgy section. They were married at the church of St Mary’s in the Butts, Reading, on 15 March 1958. During a three-year period after they were married, when they were living in ex-US officers’ accommodation on the Aldermaston Court campus, they played an active part in village life, including bell-ringing at the local church, while Pat also took part in the annual nativity play. Pat provided considerable support to Ted’s career, allowing him to focus on research. She acted as chauffeur as Ted never drove a car, and they travelled extensively together in connection with Ted’s consultancies and conferences, particularly to the USA and Canada.

When Ted Smith died in 2010, he left a legacy to the University of Manchester, endowed in perpetuity, to establish the ‘Ted and Pat Smith Prize’. The fund was set up to provide for undergraduate scholarships in engineering or science, with a preference for students studying in the field of materials.
ACKNOWLEDGEMENTS

The authors acknowledge contributions made by Professor A. H. Sherry, Professor R. J. Young, Dr D. Scarth and Dr J. R. Griffiths. The frontispiece photograph from Manchester Materials Centre was provided by Professor R. J. Young; photograph of members of the CERL Fracture section courtesy of J. R. Griffiths; photograph of portrait by Stephen Ashurst provided by Professor A. H. Sherry.

AUTHORS’ PROFILE

Michael Burdekin

Michael Burdekin is Emeritus Professor of Civil and Structural Engineering at the University of Manchester (UMIST 1977–2002). He was a Vice-Principal of UMIST from 1981 to 1983. Among various other honours, he was President of the Welding Institute from 2004 to 2006 and was awarded the Gold Medal of the Institution of Structural Engineers in 1997. He had common interests with Ted Smith in the field of fracture mechanics; the two were also involved together in the affairs of the University and Ted acted as independent internal examiner for several of FMB’s PhD candidates.

John Knott

John Knott is Emeritus Professor of Metallurgy and Materials at the University of Birmingham (Feeney Professor of Metallurgy 1996–2001) and was Dean of Engineering there from 1995 to 1998. He was awarded the Royal Society Leverhulme Medal in 2005. He was President of the International Congress on Fracture from 1993 to 1997 and was the subject of the J. F. Knott Symposium at the TMS fall meeting in 2002. He is a Foreign Associate of the US National Academy of Engineering, a Foreign Fellow of the Indian National Academy of Engineering and a Foreign Member of the Japan Institute of Metals and of the Academy of Sciences of Ukraine. He had common interests with Ted Smith in the fields of fracture and metallurgy and was a member of the Fracture section at CERL appointed by Ted Smith in the early 1960s.

Both Michael Burdekin and John Knott have held the post of Chairman of TAGSI (the Technical Advisory Group for Structural Integrity), of which Ted Smith was a member for several years.

REFERENCES TO OTHER AUTHORS

Edwin Smith

BIBLIOGRAPHY

The following publications are those referred to directly in the text. A full bibliography is available as electronic supplementary material via http://dx.doi.org/10.1098/rsbm.2017.0008 or via https://doi.org/10.6084/m9.figshare.c.3782270.