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Elected FRS 1973

BY A. HOWIE CBE FRS

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Anthony Kelly was a physicist turned materials scientist and a Vice Chancellor with a penetrating mind, tremendous energy and formidable powers of organizational engagement with both people and data. A deep understanding of the strength of materials, building up from metal crystals and their imperfections through ceramic materials, brought him into the burgeoning field of composites. In this subject, through his own pioneering research, comprehensive knowledge and long-standing inspirational role, he was a seminal figure. Through challenging times he was a very successful, reforming and long-serving Vice Chancellor at the University of Surrey and the mainspring in setting up their Research Park. Remarkably, however, he kept his own research going and continued to be very active long after his retirement, stimulating colleagues of all ages and lighting up with his interventions many a scientific meeting or more general encounter.

FAMILY BACKGROUND AND EARLY YEARS

Tony, as he was generally known, was born in Hillingdon, West London. His father, Group Captain Vincent Gerald French Kelly, was of Irish descent and taught mathematics to pilots in the education service of the Royal Air Force. His mother, Violet Vaughan, was a nurse who converted to the Catholic faith of the family. Tony remained a devout Roman Catholic with admirable charitable activity throughout his life and was made a Papal Knight in 1992. One of his fellow students at Reading was Christina Margaret Dunleavie, who became his wife in 1956 and bore him four surviving children—Marie-Clare Johnson, Paul, Andrew and Steve Kelly. At Tony’s funeral, Paul recalled the cargoes of reinforced glass nails that their early train sets carried, the competitive games for them and their friends plus on occasion some of Tony’s research students, and the stimulating family Sunday lunches at which wide-ranging
conversation in French was encouraged. Later on there were several rather demanding sailing holidays. Thanks to her natural serenity and with occasional injections of common sense, Christina exercised a calming influence on Tony’s restless energy. The loss of this tremendous partner with her death in 1997 was an exceptionally heavy blow for him.

Tony’s scientific promise became apparent at the age of 13 years in Presentation College, Reading, when he successfully corrected a physics teacher’s working on the blackboard. This episode encapsulates several of his qualities—a mind quick to spot error or inconsistency and a willingness to challenge authority. Tony’s account of the event has the impressive backing of Cardinal Cormac Murphy-O’Connor who, with his brother, was in Tony’s year, attended the same school. It was not, however, a situation where as far as we know Tony had to employ his talents to get support from his classmates! School was also the place where he recalled learning that water vapour was the predominant greenhouse gas. Since Presentation College did not have a sixth form, he had to develop his own habit for intensive study and teach himself enough physics, chemistry, geography and geology to take the University Intermediate Examination and win an open scholarship in science at Reading.

**EARLY STUDIES OF DEFORMED METALS**

Tony came to Trinity College, Cambridge, in 1950 with a first-class honours degree in physics from Reading, to join the Crystallography Research Group in the Cavendish Laboratory. This large group had been created by the Cavendish Professor Sir William Lawrence Bragg FRS to cover his wide interests in the field and was under the direction of Will Taylor, who acted as Tony’s formal research supervisor. More direct guidance in the operation of the X-ray microbeam equipment that Tony used to investigate the structure of deformed metals was provided by Peter (later Sir Peter) Hirsch (FRS 1963), who had been largely responsible for setting it up and pioneering the initial applications, although he himself was by then also studying the structure of coal. Bragg had a friendly but more intermittent involvement in the work because, apart from the distraction of his wider duties, his attention was already moving strongly towards diffraction studies of large biomolecules. As part of the 2013 Bragg centenary celebrations in Adelaide, Tony gave an interesting account (31)* of this time, spanning the years of the sensational work on DNA and haemoglobin, but making the point that Bragg’s contributions to the deformation of metals (the bubble model of dislocations as well as the microbeam work) have by comparison been somewhat underrated.

In constructing his picture of deformation in a metal, Bragg was less influenced by theoretical ideas such as G. I. Taylor’s lattice structure of edge dislocations than by direct experimental modelling (exemplified by his bubble raft simulations of dislocation motion and interactions) and by empirical evidence for the deformed structure, which pointed to a mosaic of small misoriented and strained crystal subgrains. Tony’s subsequent career demonstrated a strong resonance with this philosophy. The microbeam project sprang from Bragg’s insight that with a sufficiently fine X-ray beam, illuminating only a small number of grains, spotty rather than diffuse diffraction rings might be observed. Detailed information could be then extracted by counting the spots and measuring their shapes. In rolled aluminium, where the subgrains were comparatively large with sharp boundaries, diffraction patterns taken in back-

* Numbers in this form refer to the bibliography at the end of the text.
reflection with the 10 μm spot available yielded information about dislocation densities as a function of strain (1). Tony and Peter Gay, an older research student, successfully extended this work to a range of harder metals—copper, nickel and iron—with smaller subgrains as well as to softer metals—tin, zinc, lead and cadmium—which recrystallize at higher deformation. Tony’s first most significant innovation was to change from specimens deformed by rolling to those strained in relatively simple tensile deformation to a known stress, which could be then correlated more directly with the observed grain structure and estimated dislocation densities (2). Second, he switched from back-scattered diffraction to the use of transmission X-ray microdiffraction on thin films of beaten gold, reducing the 100-hour exposure time to about one-tenth. Third, and particularly useful in the harder metals with smaller subgrain sizes, was his use of transmission electron diffraction using a microscope operated by Dr Jim (later Sir James) Menter (FRS 1966). These advances are all recorded in his PhD thesis and are also recalled in (31), but the X-ray transmission work was more widely published only as a single image in the paper by Hirsch, Kelly and Menter (3), which mainly reported the transmission electron diffraction results. The potential usefulness of electron microscope imaging rather than diffraction was noted at the end of that paper; a further publication was promised but never appeared. By this time (1954) Tony had moved to the USA as a Research Associate at the University of Illinois and so missed out on the subsequent developments culminating in the revolutionary observation of dislocations by transmission electron microscopy in 1956. However, the knowledge of crystallography and crystal defects acquired as a research student at Cambridge remained a mainstay of his later career.

Tony soon returned to the UK to join Alan (later Sir Alan) Cottrell FRS in Birmingham and worked there in 1955–56. He then went back to the USA as an Assistant Professor and soon Associate Professor at Northwestern University in the newly opened Department of Materials Science—one of the first in the world to bear that name. The broad agenda pursued there under the leadership of Professor Morris Fine had a lasting influence on Tony’s thinking and subsequent career. He also became aware of the innovative materials development programmes being pursued by the US defence industry. For the time being, however, his personal research continued to concentrate on X-ray diffraction and the deformation of metals. A theoretical analysis of the strength of alloys containing precipitates pointed to the importance of precipitate shearing processes (4). Another paper (5) appeared describing the first of the two phenomena that bear Tony’s name—the Haasen–Kelly effect, which is the very slightly increased yield stress observed on reloading a previously strained crystal that has been allowed to relax by removing the stress. During the unloaded period, diffusion of impurity atoms to pin dislocations could be a cause of the effect, but it is generally observed at temperatures too low for diffusion to occur. The need to explain the formation of stronger traps for dislocations that have run back on unloading continues to be a challenging test of theories of plastic deformation and work hardening (Brown 2010).

Metallurgy and materials science at Cambridge

When Tony came back to Cambridge in 1959 as a university lecturer in the Department of Metallurgy, one of the first tasks given to him by Alan Cottrell was to teach an undergraduate course in ceramics. Factors here may have been his exposure to broader influences of materials science at Northwestern but also that, on his own later admission (24), he knew little
metallurgy at that time! The challenge proved to be vital in broadening out his research agenda. Although Tony’s own credentials may still have been rather slender, Cottrell’s fame attracted to the department many more excellent research students than he himself could supervise, and some of these were steered towards Tony. Having closely followed the developments in electron microscopy, Tony was swiftly able to apply them outside the field of metals to MgO (6), GeSe and graphite (7) with numerous observations of the defects produced in plastic deformation, fracture processes and radiation damage. Graphite was important through its use as a moderator in nuclear reactors and for the role that damage accumulated in it had played in the Windscale disaster. At the same time, however, Tony kept going his work on the deformation of metals with studies of precipitation and age-hardening effects.

The brilliant and wide-ranging review of precipitation hardening (8), written with Robin (now Sir Robin) Nicholson (FRS 1978), was perhaps the first clear example of Tony’s prodigious ability to embrace and make sense of a vast amount of data. As he himself said, when reviewing for *Philosophical Magazine* in 1965 the book by J. W. (Jack) Christian (FRS 1975), *The theory of transformations in metals and alloys*, such massive and imaginative data culling can involve a special form of originality. Tony was by then well versed in the use of X-rays to study alloy precipitates, and his physics background was relevant in analysing electrical resistivity data, whereas Robin at that time had a more extensive knowledge of alloys and of their study by electron microscopy. The overlap between them was therefore just right to produce a marvellous synthesis that proved to be so informative and stimulating that it became a science citation classic.

A further bonus was that the dispersion hardening work resonated with the idea of fibre reinforcement, which was already incubating in Tony’s mind through discussions with Cottrell. In celebration of Cottrell’s 70th birthday many years later, we once again have from Tony himself a detailed account of these interactions and of the subsequent developments (24). How the propagation of cracks could be inhibited in a system of strong fibres embedded in a matrix of softer ductile material was described by Cottrell in an unpublished discourse at the Royal Institution in 1960 and repeated in his book (Cottrell 1963, p. 347). The low shear resistance of the soft material would prevent sharp focusing of the forces arising from fibres that have already fractured. For interfaces weak in tension rather than shear, Cook & Gordon (1964) proposed a crack diversion process. Crucially missing, however, was any mechanism for producing ductility in such systems with a non-shearing component. In his popular article, ‘The promise of fibre-strengthened materials’ (10), Tony went beyond describing the scientific and technological challenge arising from the rapid growth of interest in these systems, and included a picture of the fibre pull-out process—presumably supplied by his research student Bill Tyson. This pull-out process (see figure 1) discovered by Tony and Tyson experimenting with a copper matrix, fibre-strengthened with ductile molybdenum or brittle tungsten wires, provided the deformation mechanism and an important new way of dissipating energy. Their report (11) with a detailed analysis of the process, including its dependence on the volume fraction and dimensions of the fibres, the individual strengths of fibres and matrix, became Tony’s most cited publication. The pull-out phenomenon provided a platform for extending a simple model previously developed at the National Physical Laboratory (NPL) by Cox (1952) to relate the differing strains in matrix and fibres to the fraction of the tensile load carried by the fibres. The analysis in (11) ignored the full complications of the complex strain fields at fibre ends or fibre-crack crossing points as well as fibre interactions but made clear the conditions for significant fibre strengthening in terms of key concepts such as the critical
transfer length \( l_c = \sigma_{fu} d/2\tau \) required for the stress transferred from the matrix to the fibres to exceed their ultimate tensile stress \( \sigma_{fu} \). Here \( d \) is the fibre diameter and \( \tau \) represents the shear strength of the matrix or of the matrix–fibre interface, whichever is smaller. Provided that the average fibre length \( l \) exceeds \( 2l_c \), the tensile strength of the composite as a function of fibre volume fraction \( v_f \) is given by

\[
\sigma_c = v_f \sigma_{fu} (1 - l_c/2l) + (1 - v_f)\sigma_m'.
\]

Here \( \sigma_m' \) is the stress in the matrix when the fibres reach their usually much greater ultimate tensile strength \( \sigma_{fu} \). Consistent with the experimental observations (in compression as well as in tension), a very useful fibre strengthening effect with \( \sigma_c > \sigma_m' \) occurs at sufficiently high volume fraction \( v_f \). The formidable problem of relating the characteristics of individual components to the key properties of a complex composite emerged in this analysis to become one of Tony’s long-term preoccupations in his drive to provide engineers with accurate predictions for composite design and performance.

Between the preliminary conference report of the work with Tyson and its full publication, Tony characteristically found time to write, with Graeme (later Sir Graeme) Davies, yet another comprehensive and very influential review (12) of fibre-reinforced metals, not only covering their mechanical strength but also discussing toughness properties and surveying the range of fabrication processes. An important bridge was thus established between the engineering/chemistry community, currently investigating the use of fibres of glass, carbon and even boron (mainly for defence purposes), and the academic world of metallurgy. Through a consultancy at Farnborough, Tony was in close contact with the carbon fibre work there (Watt et al. 1964). With the parallel attack already mentioned that he was pursuing on the properties of graphite as well as of ceramics and other strong solids, he was excellently poised to build further on this situation.

Tony’s interest in the ductility of crystals had already been developed in joint work with Geoff Groves (9), which is still quite frequently cited. Here a simple method was presented to decide whether the number of physically distinct slip systems in a given

Figure 1. Copper matrix with tungsten fibres showing pull-out after deformation and fracture. (Reproduced by courtesy of Professor W. R. Tyson from his PhD thesis (Tyson 1964).)
crystal could constitute the five independent systems required for ductility according to the von Mises yield criterion. Again with Tyson and now joined by Cottrell, Tony then made a significant further advance in assessing whether a crystal can break in a fully brittle fashion or whether some plastic flow must accompany fracture. Assuming that the state of stress near a crack is one of biaxial tension and plane strain, they pointed out that the ratio $R$ of the maximum tensile stress to the maximum shear stress is then governed only by the (possibly anisotropic) value of Poisson’s ratio. They then proposed that a crystal will be inherently brittle when $R$ exceeds $S = \sigma_i / \tau_i$, the ratio of its ideal tensile strength to its ideal shear strength. Because $S$ involves crystal properties such as surface energy in addition to elasticity, this criterion goes significantly beyond the simple correlation between malleability and Poisson’s ratio suggested earlier (Pugh 1954) and which is still employed for metallic glasses. The 1966 paper (13) describing this theory with a full discussion of its success and limitations for different materials proved to be very influential and stimulated a vast amount of later work, particularly on topics that it had so successfully skated over such as the precise role of dislocations in blunting the crack tip and the atomistic structure of the tip region.

Not content with the two influential review articles already mentioned and several shorter articles for a still more general audience, Tony then found time to produce two highly successful textbooks. In *Strong solids* (14) he discussed the theoretical strength for both cleavage and shear of a perfect crystal for a wide range of materials, followed by a detailed description of the influence of flaws such as cracks and dislocations. Reflecting the situation at that time, major attention was given to the practical methods, such as dispersion hardening, for achieving high strength in metals and their alloys. Informed, however, by the recent work described above, the chapter on fibre reinforcement broke radically new ground. A concluding chapter on production and properties of composite materials placed valuable emphasis on related themes destined to grow in importance. *Strong solids* was swiftly recognized not only as a valuable compendium of existing data but also as a pioneering exposition of this material in the context of the theory of defects in solids, and the newer field of fibre reinforcement.

Tony’s Cambridge experience both as student and teacher illuminated a gulf between classical crystallography, well established for perfect crystals, and the much more recent subject of crystal defects, often taught and studied by people with little knowledge of the essential crystallography. *Crystallography and crystal defects* (16), written with Geoff Groves, addressed this problem brilliantly and became a standard text both for teaching and for reference.

With another research student, George Cooper, Tony capped this prolific decade in Cambridge with further investigations of the fracture mechanics of composites (15). His subsequent analysis of this work and review of the important role of the pull-out phenomenon in increasing fracture toughness made clear that the work of fracture was proportional to the fibre diameter $d$ and increased with fibre length $l$ up to a maximum value at $l = l_c$, decreasing thereafter (17). In his PhD thesis, Cooper (1966) also reported pioneering experiments with a brittle matrix composite. Carbon-coated silica fibres, with a unique strain to failure of 4%, were incorporated into a resin with a strain to failure of 6% at room temperature and 1% at 77 K. With this obvious contrast between the failure strains of fibre and matrix, the behaviour of the composite was quite different at these two temperature extremes. At 77 K in particular, the matrix broke in a series of parallel cracks (see figure 2) and was no longer continuous, whereas the fibres remained intact and bore the load. A useful effective ductility
up to an overall composite strain of 5% had been produced in a system of entirely brittle materials! The wide-ranging significance of this multiple fracture discovery was possibly not immediately apparent, and it was not published beyond Cooper’s PhD thesis. However, it laid the foundation for the next chapter of Tony’s work, at the National Physical Laboratory (NPL).

**NATIONAL PHYSICAL LABORATORY**

Tony was appointed in 1967 to the NPL post of Superintendent of the Division of Inorganic and Metallic Structure. He was then promoted in 1969 to be Deputy Director in charge of the Materials Group (comprising 4 of the 12 NPL divisions). Although his own administrative burden inevitably increased, he thus had access to wider capabilities in the fabrication and testing of novel composites and a more effective platform for industrial contact.

The subject of composite materials was the main item on Tony’s research agenda at NPL and two of his Cambridge students (George Cooper and Rayner Mayer) followed him there as the nucleus of a larger team, including John Aveston (a chemist), Graham Sims, John Sillwood and later Neil McCartney (a mathematician). Following up the ground-breaking initial observations made by Cooper as a research student in Cambridge, the most important composite work developed at NPL was the investigation of multiple fracture in brittle matrices. The Aveston–Cooper–Kelly (ACK) theory of multiple fracture was first published in an NPL conference report (18) and later in a more detailed journal paper (19), both of which attracted a large number of citations.

When the strain to failure of the fibres exceeds that of the matrix, they remain intact bridging the many cracks in the matrix and will still be able to carry the extra load \( \Delta \sigma_f \) provided that

\[
\Delta \sigma_f = \sigma_{mu} (1 - v_f) / v_f < \sigma_{fu} - \sigma'_f.
\]

Here \( v_f \) is the volume fraction of fibres, \( \sigma_{mu} \) and \( \sigma_{fu} \) are the ultimate tensile stresses of matrix and fibre, respectively, and \( \sigma'_f \) is the stress in the fibre just before the matrix cracks. The critical
volume fraction that must be exceeded for this to occur is therefore given by

\[ v_f = \frac{\sigma_{mu}}{\sigma_{fu} + \sigma_f' - \sigma_{mu}} \approx \frac{\sigma_{mu}}{\sigma_{fu}} \]  

and can be quite small because usually \( \sigma_{fu} \) greatly exceeds \( \sigma_{mu} \) or \( \sigma_f' \). The resistance to catastrophic cracking in many common brittle solids such as cement can thus be markedly improved by the addition of steel, glass or asbestos in amounts of only 1% or 2%. ACK theory thus explained the properties of fibre reinforced cements and concretes, underpinning the whole development of ceramic composite materials as well as contributing to the understanding of the modes of toughness of laminated composite structures with resin matrices.

A force balance relation, rather similar to that used to define the critical transfer length mentioned above, shows that the limiting separation of the cracks lies between \( x' \) and \( 2x' \), where

\[ x' = \frac{\sqrt{(1 - v_f)}}{2v_f} \left( \frac{\sigma_{mu} d}{4 \tau} \right) \]  

Here, as previously, \( d \) is the fibre diameter and \( \tau \) is the shear strength of the matrix or matrix–fibre interface, whichever is smaller. Experimental observations confirmed the dependence of crack spacing on \( d \) at not too small values and on \( \tau \) when independent knowledge of this was available. However, in a more detailed investigation, Cooper & Stillwood (1972) found anomalously large values of \( x' \) at very small fibre diameters or large volume fractions corresponding to small separations \( s \approx d/v_f \) between fibres. Because \( s \) effectively sets an upper limit for the length of any pre-existing Griffith crack in the matrix, the first cracking stress \( \sigma_{mu} \) appearing in equation [4] is increased at small \( s \) by the presence of the fibres. In short, if the inter-fibre spacing becomes sufficiently small, the fibres exert such a grip on the matrix that it is unable to crack. The initiation of the multiple fracture process is then hindered, permitting a still further enhancement of the mechanical properties of the ceramic matrix composite.

In 1973 a two-year secondment from NPL to work at ICI under a government–industry–academia task force gave Tony an opportunity to develop industrial contact at first hand. In this capacity he successfully opened up new links for ICI with academic research not only in composites but also for example in the electron microscopy of catalysts. Tony’s involvement with NPL did not cease with his next move, to Surrey. His encouraging but challenging style of engagement with younger colleagues facilitated continuing research collaborations on composites with several staff members, notably Neil McCartney. He influenced NPL funding through his chairmanship of the Department of Industry Engineering Materials Requirements Board. Later still, when NPL was operated under a contract with Serco, Tony served as a member of their Management Board. He would have been intrigued to learn that, under the latest reorganization, NPL is now run with formal involvement of two universities—Surrey and Strathclyde.

**University of Surrey**

In his 19 years (1975–94) at the University of Surrey, Tony Kelly set the record for the longest-serving Vice Chancellor and drove forward many revolutionary changes there. Several accounts, much fuller than can be given here, are available (see, for example, http://www.surrey.ac.uk/files/pdf/CHAPTER%202.PDF). To summarize, however, he succeeded in a
time of severe financial stress in diversifying the university’s income stream, particularly in research, and increasing it more than tenfold. At a meeting of Vice-Chancellors in Downing Street, he was apparently told by Margaret Thatcher, ‘You can have money for a Readership, Dr Kelly, but not for a Professorship—like it or lump it.’ With his formidable intellectual energy, he set about educating himself for the detailed planning discussions needed in a wide range of academic fields. Some departments had to be closed, but the number of students more than doubled, and he encouraged new ventures such as dance instruction. Most relevant for this account was his success (25) in starting the Surrey Research Park. The idea arose during a stimulating sabbatical visit that Tony made to Switzerland in 1979, and was driven forward with the able support of both the secretary and the treasurer of the university. A particularly crucial decision was to resist the pressure to hand over the development to others but, at the expense of sleepless nights, to keep it in the hands of the university. The University of Surrey was consequently placed in a much more secure long-term financial position with a greatly enhanced research profile.

Most remarkably amid such intense administrative duties, Tony managed to maintain his scholarly output through some 80 publications, with just a few on traditional topics for the Vice Chancellor’s desk. His characteristically radical alternative funding scheme for higher education (described at a Public Finance Foundation 1990 discussion meeting) included a student loan element but was mainly focused on leaving maximum freedom of choice to both the universities and the students. Ranging more widely, Tony took it as a great honour to be invited by the Linguistic Society to be their 1988 Treford lecturer and put a tremendous amount of work into preparing his published address on ‘Science, technology and language’ (22). Of potential value for any future history of materials science are a variety of significant accounts of developments and future prospects as well as his in-depth tributes to several departed colleagues. A third edition of *Strong solids* was produced, jointly with his former Cambridge research student N. H. MacMillan. This volume preserved the original comprehensive and unified view but was greatly expanded to include new sections on strong ceramics and production methods for fibrous solids. The highly successful *Concise encyclopedia of composite materials* (23) emerged in 1989 (updated in 1994) and, with closely integrated and cross-referenced articles by more than 70 authors, is a strong testament to Tony’s role as sole editor as well as author of five contributions. Yet another encyclopedia on *Fabrication of composites* (20) appeared in 1983, edited jointly with Sergei Mileiko. Continuing this theme in ‘Composites for the 1990s’ (21), Tony speculated (with numerous examples) that ease of fabrication could by itself be a justification for the use of composites and that the traditional role of composites in surpassing the mechanical properties of the individual constituents might be extended to thermal, electrical and optical properties. Although never of a merely incremental nature, some of the research papers emerging from the Vice Chancellor’s office reported progress in the composites field that he had explored previously, such as further work on the tensile first cracking strain with Aveston and on mechanical properties with Chou. Others involved more radical breaking of new ground, such as the investigation (26) with J. G. Parkhouse of random packing of fibres in three dimensions underpinned by experiments with raw spaghetti (figure 3). From 1988 to 1999, as a member of the Rolls-Royce Advisory Board, Tony had a very practical opportunity to deploy his knowledge of ceramics and composites. At a time when a whole range of materials was being considered for potential applications in aero-engines, his expert advice to the company was extremely valuable.
Although he enjoyed his influential role as Vice Chancellor and the platform it provided for social interaction and entertaining, Tony’s idiosyncratic personal style frequently emerged. During an occupation of the university centre, the student protesters who were using his office as a coffee lounge were surprised to find the Vice Chancellor dropping in for refreshment and a chat. Their surprise may have been shared by Tony’s senior colleagues engaged in the delicate negotiation task. Similarly, the university servant who brought a wake-up cup of tea to overnight guests at the Vice Chancellor’s residence was their host in his pyjamas. Possibly some guests failed to appreciate this kindness or, more likely, Tony ruffled too many feathers in the civil service or at the University Grants Committee to be awarded the knighthood that many thought should have been his due for his work at Surrey. The photograph reproduced in figure 4 was taken when Queen Elizabeth visited the university in March 1992. In these years, sailing (see figure 5) offered Tony an invigorating break, although as captain of his own boat he was still in charge.

‘Retirement’ in Cambridge

Materials science

On his retirement from the University of Surrey in 1994, Tony returned to live in Cambridge, becoming a Distinguished Research Fellow in the Department of Materials Science. The
Figure 4. Visit in 1992 of Her Majesty The Queen to the University of Surrey accompanied by the Duke of Kent as Chancellor and received by Tony and Christina Kelly. (Reproduced with qualified permission of the University of Surrey; see the acknowledgements.) (Online version in colour.)

Figure 5. Sailing back to Largs from Loch Fyne. (Photograph taken by the author.) (Online version in colour.)
Biographical Memoirs

department benefited greatly from the collaborations he developed there, but his influence in the wider materials science world continued to grow through his infectious enthusiasm for the subject and energetic participation in many conferences. He became an inspirational figure for many younger colleagues and in 1999 gave the first of an ongoing series of annual lectures bearing his name and delivered in the department by internationally distinguished materials scientists.

His investigations of the possibility for constructive engineering of the thermal expansion properties of composites demonstrated his continued ability to focus impressively on some special feature in a complex field of data (28). With Neil McCartney, although apparently as junior author, he produced at this late stage easily his most mathematical paper, dealing with the application and extension of Maxwell’s effective medium theory to describe the mechanical and thermal properties of composites (29). At the other extreme, he also wrote a full and most interesting account of his early career and of his role in the development of composite science (27). For the substantially updated second edition of *Crystallography and crystal defects* produced in 2012, Tony was fortunate to find Kevin Knowles as co-author.

**Climate change**

In the last decade of his life, Tony became deeply suspicious of the reliability of the forecasts from climate experts about the occurrence of man-made global warming and of the appropriateness of some of the actions to deal with the problem. His school memory that water vapour was the most important greenhouse gas was possibly a starting point, but with his customary energy he set about educating himself through wide reading and consultation with a range of experts. He had some difficulty getting his views published, but eventually his first paper appeared in *Energy and Environment* (30). In parallel with this, he organized in 2010 a letter to the Royal Society signed by 43 of its Fellows successfully petitioning the Society to change its public stance on the subject.

Tony then broadened the debate to include ethical issues by arguing that the steps being taken to address possible problems of climate change were certain to make conditions even worse for the poor people in the world. Characteristically he planned to present this view at an impressive discussion meeting he had organized under the chairmanship of the former Archbishop of Canterbury, with speakers from science and government on both sides of the climate debate. Unfortunately he had a stroke a few weeks before the meeting but was able to entrust his son Paul to deliver his address. This has subsequently appeared as a report of the Global Warming Policy Unit (32). Jointly with Michael Kelly FRS, Tony co-authored a further detailed critique of the consensus view on global warming that is now submitted to *Energy and Environment*. Michael Kelly’s words describe Tony’s lifetime attitude not just to climate change but also to science more generally:

> He was a scientist of the old school, who took ‘Nullius in verba’ as a matter of daily practice. He was properly sceptical until the real world confirmed his or others’ ideas. He was not impressed by the modern tendency to use incomplete data to weave elaborate stories that could be undone by hard data, or worse, were not capable of falsification.

Tony’s altogether outstanding record in organizing and participating in Royal Society Discussion Meetings as well as his long and active membership of the Royal Society Dining Club are further testimony to his enthusiasm for energetic open debate that was both broad-ranging and rigorous.
Anthony Kelly

Churchill College

Tony joined Churchill College in 1960 as a Founding Fellow and Director of Studies in Metallurgy and Materials Science, also acting as secretary of the Wine Committee until he left for NPL in 1967. Having been made an Extraordinary Fellow in 1989, he returned to the college on his retirement from the University of Surrey and later became a Pensioner Fellow. His long service on the Archives Committee as well as on the Wine Committee is just a token of the great influence he exercised. In his 14 years as editor, the annual Churchill Review was radically reshaped. Many memorable parties were held at his home close by in Madingley Road, where two of the pictures reproduced in this memoir were prominently displayed together with an impressive collection of marine paintings. With the death of Christina, the college became an even more important part of Tony’s life. In a remarkably imaginative and greatly appreciated gesture he set up and endowed the Christina Kelly Memorial Fund to provide dining privileges for the widows (or widowers) of deceased Fellows.

During Tony’s lifetime the craft of composites developed from its ancient roots in Roman concrete and horsehair-reinforced mortar through high-tech defence applications to the consumer marketplace. Although he arrived some centuries too late to be the father of composites, he could be regarded as the father of composite science because at a crucial juncture he pioneered well-aimed academic research to reveal some of the basic phenomena, and his energetic scholarship did much to shape the field. His hip and knee replacements in later life enabled him to test at the most personal level our success in mimicking nature’s composites. With the astounding pace of commercial development, it will be a challenge to keep open the window that Tony created for academic research and understanding to influence this burgeoning field.

Tony managed his final leave-taking with consummate skill. A fall in church heralded the onset of a heart problem but he took time in the next two days to summon a few friends for consultations on current business and to puzzle them slightly by shaking hands as they left. He died in his sleep in his own bed that Tuesday night. Supplementing a published tribute from his colleagues (McCartney et al. 2010), the college celebration of Tony’s 80th birthday included a poem shaped like an inverted bottle of one of his choice wines. Reconstructed lines just from the neck region of this now broken vessel are offered here in conclusion:

...............endured some savage knocks
But wit and penetrating mind preserved.
  His nature held
  Like composites
  A hard–soft meld
  Fused opposites.
  At heart benign,
  This critic fierce
  Had tough design
  The truth to pierce.
  Some fresh crusade
  He’d try each day
  You to persuade –
  He’s had his say.
Honours

1973 Fellow of the Royal Society
1979 Fellow of the Royal Academy of Engineering
1986 Foreign Associate of the National Academy of Engineering, USA
1988 CBE
Honorary Fellow of the Institute of Linguistics
1990 Member of the Academia Europaea
1992 Knight of St Gregory
1993 Deputy Lieutenant, Surrey
1996 Honorary Fellow Institute of Structural Engineers
1996–67 President of the Institute of Materials
1997 Honorary Fellow Institute of Civil Engineers

Awards

1967 William Hopkins Prize, Cambridge Philosophical Society
Beilby Medal Royal Society of Chemistry
1974 A. A. Griffith Medal, Institute of Materials
1984 Medal of Excellence, University of Delaware
1988 Telford Lecture, Linguistics Society
1991 International Gold Medal, American Society for Materials
1992 Platinum Medal, Institute of Materials
1995 Humphry Davy Lecture, Royal Society
Bakerian Lecture, Royal Society
1999 Lee Kuan Yew distinguished visitor to the Commonwealth of Singapore
2000 Acta Metallurgica Gold Medal
2003 Alfred Ewing Medal, Institute of Civil Engineers
2004 UK–Canada Rutherford Lecture, Royal Society
2011 President’s Medal, Royal Academy of Engineering

Tony Kelly was awarded honorary degrees from the following universities: Surrey (1994), Birmingham (1997), Hanyang, S. Korea (2001), Reading (2002) and Navarra, Spain (2003). In 1975 he was a founding member of the International Conference on Composite Materials, an ongoing series of conferences, of which 18 have been held to date. He was a member (1973–75), then chairman (1976–80), of the Department of Industry Engineering Materials Requirements Board and was a member of the Rolls-Royce Advisory Board (1988–99). He was also a Director of Johnson Wax Ltd from 1981 to 1996, of QUO-TEC Ltd from 1984 to 2000 and of NPL Management Ltd from 1995 to 2001, and was chairman of Surrey Satellite Technology from 1985 to 1995.

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The frontispiece photograph was taken by Godfrey Argent and is reproduced with permission.

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McCarty, L. N., Clegg, W. J., Mortensen, A. & Smith P. A. 2010 Editors’ introduction to a collection of papers to celebrate the 80th birthday of Professor Anthony Kelly, CBE, FRS. Phil. Mag. 90, 31–32.

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Biographical Memoirs


(19) 1983 (Editor, with S. T. Mileiko) *Fabrication of composites (Handbook of Composites, vol. 4)*. Amsterdam: North-Holland.


