BIOGRAPHICAL
MEMOIRS

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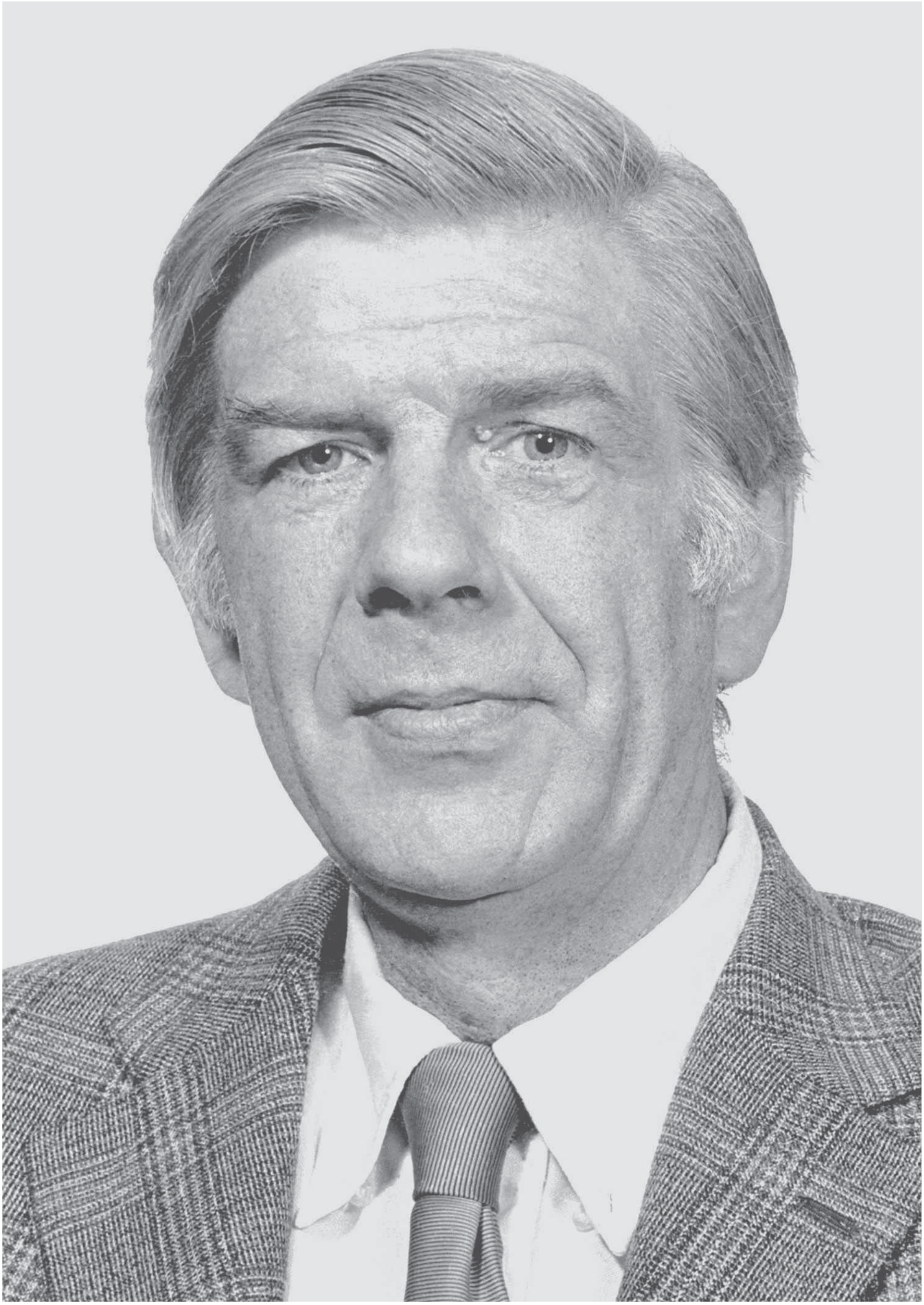

J. W. Christian

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Elected FRS 1975

By George D. W. Smith[1] and Harshad K. D. H. Bhadeshia[2]

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Introduction

During a distinguished career, John Wyrill ('Jack') Christian had a profound impact on the subject of materials science, particularly physical metallurgy. He was recognized as a world authority on martensitic transformations, and laid the foundations for the modern understanding of this topic. His monumental two-volume work, *The theory of phase transformations in metals and alloys*, is the classic authoritative treatise on the subject, and remains one of the most important texts ever published in the area of materials science. It redefined the whole field of phase transformations, set new standards of intellectual rigour and comprehensiveness, and inspired successive generations of scientists to follow in his footsteps. He was also a pioneer in the study of the mechanical properties of metals and alloys, particularly those having the body-centred cubic structure. He and his students played a key role in establishing that the low-temperature mechanical properties of this important class of metals are controlled by intrinsic dislocation–lattice interactions and not by impurity effects. He contributed to the study of many other topics in materials science, including the structure of interfaces, the mechanism of deformation twinning, and the properties of stacking faults. He was the recipient of numerous national and international awards for his work. His researches, which were always characterized by precision and deep physical insight, have stood the test of time.

Jack will also be remembered for his outstanding personal qualities of gentleness, kindness, modesty, good humour and consideration for others, which endeared him to students everywhere, and to colleagues from around the world. It was often said of him that he had

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many friends and no enemies. He played a major role in the development of the Department of Materials at the University of Oxford, and showed exemplary courage and fortitude in facing the ravages of a serious and debilitating illness for more than two decades. He was the 'teacher of the teachers' in his field, one who inspired people as much by his personal character as by his intellectual achievements.

Early life

Jack Christian was born in Scarborough, Yorkshire, on 9 April 1926. His father, John William Christian, was a trawler skipper and also skipper-lieutenant in the Royal Naval Reserve. His mother was Patience Louisa Christian (*née* Crawford). He had one sibling, a younger brother, Donald, who died in 1982. Both of his grandfathers were fishermen. His father was unemployed for much of the time during the economic depression of the 1930s, and was absent for most of World War II on minesweeping duties. Despite these difficulties, Jack's memories of his childhood were very positive:

> My childhood was a very happy one. I was fortunate to live in a delightful seaside town, to have good friends, and to attend an excellent school. Some of my happiest memories are of the annual Cricket Festival which as a small boy I attended for every minute of the nine days play. My Dad was a very loyal supporter of the Scarborough football club and at one period in my childhood I went with him regularly to watch the Saturday home games. My parents were not well off, but they were not devastatingly poor and they ensured that my brother and I had the best opportunities to have a good life.

Jack's strongly held views on social justice, human rights, fairness and equal opportunity for all were almost certainly based on his experiences during these early years.

Jack was educated at Central School, Scarborough, and Scarborough Boys High School (1936–43). He passed the high school entrance examination a year earlier than usual and proceeded through the rest of his education a year ahead of schedule. He participated in many activities at the High School, including debating, drama, soccer and rugby. He was particularly pleased to get his school colours in rugby at the early age of 15 years, and to play the parson in Bernard Shaw's *The devil's disciple*. He retained this wide range of interests for the rest of his life.

Jack recalled how his interest in science was awakened in high school:

> I was taught Physics for the whole of my time there by Cyril Isherwood, who was a deservedly popular master and managed to convey some of his love of Physics to the boys. I had no sense that I might become a scientist through most of my school career, however, and after the School Certificate results it was a toss up whether I should enter the Science Sixth Form or the Modern Sixth Form. I was much influenced by the Mathematics teacher, a young man named Wilmut. He had an amazing facility for working out difficult problems on the blackboard, and his enthusiasm was contagious.

Jack eventually took the Higher School Certificate in mathematics, physics and chemistry, and in 1943 he won state and county major scholarships, which enabled him to go up to The Queen's College, Oxford, at the age of 17 years to study the accelerated wartime degree course in physics and radio. He obtained a First Class in Honour Science Moderations in 1944, and was made an Honorary Scholar at Queen's. He completed the shortened physics degree

course in 1945, graduating with honours at the age of 19 years. He described the next step in his career as follows:

> In 1945 it was evident that the war in Europe was ending and a few scientists were encouraged to begin University research instead of entering either the services or industry. Hume-Rothery wished to appoint two physicists to his science of metals research group in the Inorganic Chemistry Laboratory and Stephen Carlile and I were selected. Later in the year, the relevant Government Ministry decided to allow about six Oxford physicists to spend a third year reading for Full Physics finals, and I was offered this as an alternative. All my instincts were to accept this offer, but HR made a tremendous fuss and persuaded me to refuse it. This was undoubtedly my most difficult early career decision and for many years afterwards, I was convinced that I had made a mistake since it cut me off from mainstream Physics at Oxford. In retrospect, however, I am very glad that I became a Physical Metallurgist.

Oxford research and teaching: the beginnings

The research group of W. Hume-Rothery FRS occupied two overcrowded rooms on the ground floor of the Inorganic Chemistry Laboratory (ICL), one of which (room 6) contained a special vibration-free potentiometer bench, numerous furnaces for heat treatment, a travelling microscope for measuring X-ray films, and in one corner, shielded by a sheet of lead mounted on a table, a Metropolitan–Vickers X-ray unit. As time went by, the number of connections to the potentiometer increased, and the laboratory took on a distinctive appearance (figure 1).

Hume-Rothery described this room as ‘a nightmare’. It was in these surroundings that Jack conducted his work. He described his early research experiences as follows (an edited version of his original words):

> The Physics course at Oxford consisted of straight Physics + Radio, the latter being added for wartime purposes. So I knew nothing of Metallurgy when I joined Hume-Rothery. His basic interest was in the determination and then the interpretation of metallurgical phase diagrams. Stephen Carlile and I were given the task of initiating research on high melting point refractory metals of the first transition period and the equilibrium phase diagrams of their alloys. We were to determine initially the chromium–manganese diagram as representative of these high melting point alloys. This work involved several techniques new to HR’s group, e.g. high temperature, high vacuum induction melting. We went to the National Physical Laboratory for a few weeks to assist in their electrolytic method of producing pure chromium and to acquire some general expertise in high temperature work. In Oxford, we constructed a high vacuum induction furnace in which we melted the alloys and undertook thermal analysis. We were actually paid by the Ministry of Aircraft Production (later incorporated into the Ministry of Supply). The salary was adequate but scarcely generous and we became connoisseurs of ‘British Restaurants’ of which there were several in Oxford. These were a war-time invention; canteens serving basic and rather stodgy food very cheaply; the initial price of a main course was one shilling. There were long queues at lunch and dinner, often composed largely of other research students, but eating in them was good fun. We completed our D.Phils. after the usual struggles and our thoughts turned to what to do next. Stephen left for a research post with Mond Nickel but HR asked me to stay on and generously allowed me to choose the subject of my continuing research. I thought phase diagrams were very dull stuff and had become interested in various aspects of what was then called ‘Metal Physics’. So I did a little calculation on the thermodynamic functions of pure manganese and then worked on cobalt which had a very interesting solid state phase transformation. I managed to link this

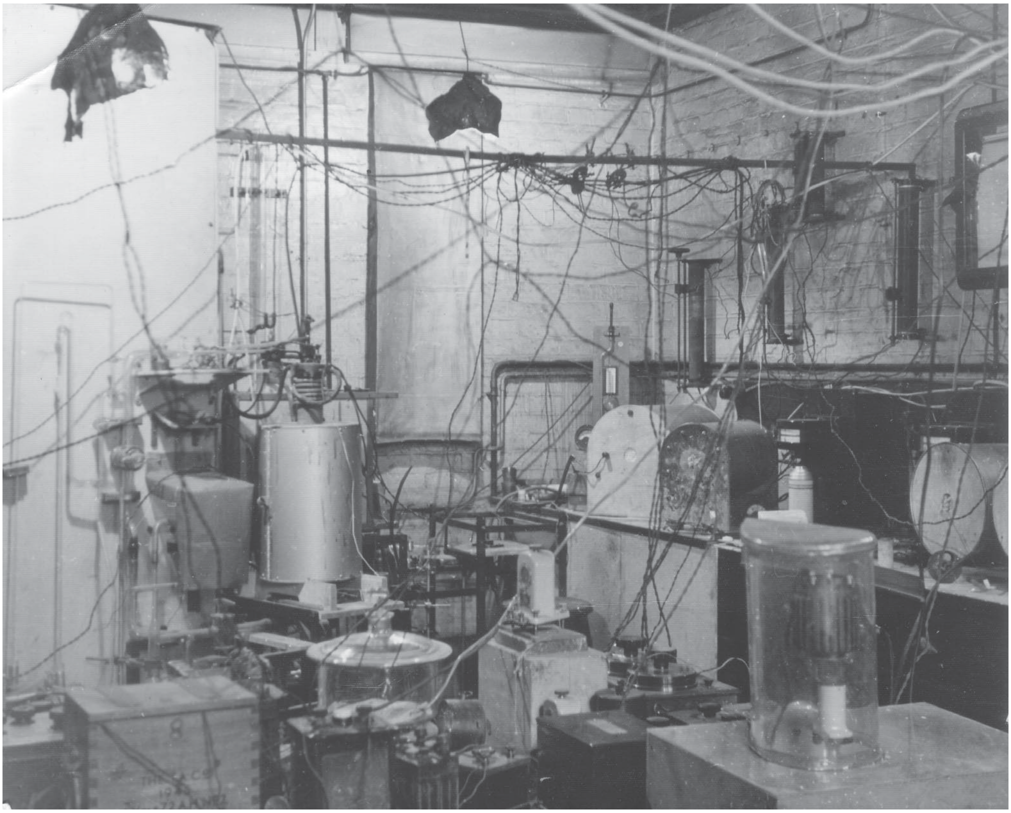

Figure 1. Room 6 in the Inorganic Chemistry Laboratory at Oxford, where Jack Christian conducted his early research on equilibrium phase diagrams of refractory metals (*ca*. 1951). (Photograph taken by Donald Hawes and reproduced courtesy of the Institute of Materials, Minerals and Mining, London.)

to properties of dislocations and this was my first important paper, published in *Proc. Roy. Soc.* I became more generally interested in martensitic transformations via an intriguing micrograph in my D.Phil. work which led me on to consider the phase transition f.c.c.–f.c.t. [face-centred cubic to face-centred tetragonal] in manganese–copper alloys. About this time I was given my first research student Z. S. Basinski [later to become Professor Basinski]. He read Chemistry at Oxford and came to Hume-Rothery's laboratory as a Part II (fourth year) student. He worked on the transformation in Mn–Cu alloys for his Part II project, showing the highly twinned nature of the product phase and making many observations relevant to the mechanism. He worked on the analogous system In–Tl for his D.Phil. This was low-melting and much easier to study than Mn–Cu. He was able to grow single crystals and to obtain single interface transformation and we studied the deformation behaviour of transformed single crystals. We worked with the highly twinned structures which were produced by the martensitic transformation and showed how they could be a mode of deformation with all kinds of intriguing properties which were later called shape memory.

About this time, Wechsler, Lieberman and Read in the USA and Bowles and Mackenzie in Australia independently published their general theories of martensite crystallography which had a tremendous impact on the subject and are still used today. My own contribution was very modest, but I was able to prove the equivalence of these two theories despite their very different

> mathematical formulations, and I went on to write a review paper with Professor B. A. Bilby of Sheffield University which was presented at a Phase Transformation conference organized by the Institute of Metals in 1956.

It was during the period 1951–56 that Jack's international scientific reputation became firmly established. His early papers on martensitic transformations in cobalt (1)*, manganese–copper (2) and indium–thallium alloys (5, 6), soon became recognized as classics in the field. As described above, he moved on to consider the crystallographic theory of martensite more generally. In 1956, together with Professor Bruce Bilby (FRS 1977), he produced a landmark review on the subject, which was presented at a Phase Transformations conference in London (7), and he published two closely related papers in the *Journal of the Institute of Metals* (8, 9). From 1956 onwards he developed a second field of interest, in the mechanical properties of body-centred cubic metals and alloys, and became a world-leading researcher in that field as well. His achievements in each of these fields of research are described in more detail below.

It is important to emphasize that although Jack was ultimately recognized primarily for his theoretical work on phase transformations and mechanical properties, he was also an experimentalist. He co-authored a book with Hume-Rothery and Pearson (3) on the experimental determination of metallurgical equilibrium diagrams. Hume-Rothery bore testimony to Jack's experimental skills in a letter to K. C. Turpin, the Secretary of Faculties at the university, at the time of the appointment of his DPhil thesis examiners:

> My research student, J. W. Christian, of Queen's … is an exceptionally good man and has done really splendid work in fitting up a laboratory for high temperature research and in working out an equilibrium diagram of very difficult metals.

This close familiarity with experimental research was of inestimable value to him in later life. His theoretical work was always linked to well-designed and incisive experiments.

Jack was appointed departmental demonstrator in metallography in 1948, and initially began lectures on metallurgical topics to chemistry students, who were able to register for metallography as a supplementary subject in their Final Honour School. He was elected to a Pressed Steel Company Research Fellowship in 1951. In 1954, the same company endowed a readership in metallurgy named after their Managing Director, George Kelley, and Hume-Rothery was appointed to this position. In 1955, Jack was appointed as Oxford University's first lecturer in metallurgy.

The Department of Metallurgy at Oxford

The idea of a separate Department of Metallurgy at Oxford developed gradually. The original plan had been to establish a postgraduate research institute. However, the feedback received from industrial employers and potential sponsors was that there was a critical need to increase the supply of graduates in this field, and so the plans were extended to include an undergraduate degree course. Jack became deeply involved with Hume-Rothery in planning the Honour School in Metallurgy, which was finally approved by the university in 1955. At that stage, the Honour School was designed as an offshoot of the existing chemistry degree course, with

* Numbers in this form refer to the bibliography at the end of the text.

organic chemistry being replaced by the study of the science of metals, and with the fourth year (Part II) being devoted to a metallurgical research project. Early in 1956, Jack was granted six months' leave of absence to work at the National Research Council Laboratory in Ottawa, Canada. This was arranged with the encouragement of the external sponsors of the new department, who thought it desirable for him to visit similar establishments in North America and learn what he could about modern American practice in this newly emerging field. Both the Honour School and the department officially commenced operation in October 1956. Funding was obtained from the Wolfson Foundation for a chair in metallurgy, and Hume-Rothery was installed as the first Isaac Wolfson Professor of Metallurgy in 1957, after which Jack was appointed to the George Kelley Readership in 1958.

Jack was active in the planning of the first new building for metallurgy in Oxford (now known as the Hume-Rothery Building), which was opened in 1959. He continued to play a key role in the development of the department over the next 30 years. During that time he performed a wide range of teaching and administrative duties with immense good humour, tact and efficiency. After the retirement of Hume-Rothery in 1966, Peter (now Sir Peter) Hirsch FRS moved from Cambridge to become Head of Department, a position that he occupied for the next 25 years. Jack gave him complete support throughout this period of sustained expansion of the Oxford department, most notably taking a leading role in the comprehensive redesign of the undergraduate degree course, and its broadening to include a much wider range of materials, including ceramics, polymers, composites and functional materials such as semiconductors, superconductors and magnetic materials. He chaired the Academic Course Committee for many years and prepared the submission for the accreditation of the undergraduate degree course by the Institute of Materials. He served as Acting Head of Department on several occasions when Hirsch took sabbatical leave, and acted as Hirsch's deputy for two years when he was appointed as part-time chairman of the United Kingdom Atomic Energy Authority (1982–84). He was elected to a Fellowship of St Edmund Hall in 1963, and to a professorship in physical metallurgy in 1967.

Jack held the professorship until he took early retirement in September 1988, under the Oxford Mobility Incentive Scheme (OMIS). He famously remarked that, in his case, the scheme had 'signally failed in its objectives'. He was back at his desk the next morning, and continued to work actively as an Emeritus Professor until the day of his death in 2001.

Research on martensite and bainite transformations

In 1951, at the age of 25 years, Jack published his seminal paper in *Proceedings of the Royal Society* on the subject of the cobalt transformation, in which he showed by thermodynamic arguments that the faults in the hexagonal structure can be explained without assuming them to be in thermal equilibrium (1). Indeed, such faults, consisting of 'half-dislocations', could in the cubic form explain the difficulty in understanding how the shearing associated with martensitic transformation begins. In other words, he proposed a mechanism for the nucleation of martensite.

Aside from the shear, the changes in the lattice result in alterations of density. Jack was delighted when Brooks and co-workers at Birmingham University produced the first observations of the volume change associated with individual stacking faults in stainless steel (Brooks *et al.* 1979). These observations showed uniquely that the density change is due to a dilata-

tion normal to the fault plane, precisely as would be expected for martensitic transformations which cannot tolerate dilatational strains parallel to the habit plane on a macroscopic scale. Thus, the fault does not simply involve shear on the fault-plane, but also a volume change, which is normal to that plane and leaves it invariant. The deformation is known therefore as an *invariant-plane strain*. Of course, once a particle is nucleated, it has to grow and Jack was able to show that this could occur via a dislocation pole mechanism.

The transformation in cobalt is especially simple in that dissociation of half-dislocations changes the lattice and the resulting microscopic deformation is identical to the shape strain observed macroscopically during transformation. Strangely, this was not the case for most other systems where the observed shape deformation was inconsistent with the crystal structures of the parent and product phases. To add to the difficulty, the invariant-plane of the martensite and its orientation relationship with the parent were measured to be irrational. This puzzle was solved by the independent mathematical theories published by Wechsler *et al*. (1953) and by Bowles & Mackenzie (1954*a*, *b*) and Mackenzie & Bowles (1954). Wonderful as they were, the theories contained complicated mathematics, which Jack assimilated; he was the first to reveal their essential similarity. Not only did he do so, but he was, through his lectures, able to communicate the elegance of the work with breathtaking simplicity.

An adaptation of the diagrams he used is presented in figure 2. The parent phase is labelled 'austenite' (a); the observed change in the shape of the crystal when it transforms to martensite is illustrated in (b). But this deformation, when applied to the austenite, does not produce martensite. To obtain the correct crystal structure of martensite it would be necessary to add a further deformation (c), but that deformation has somehow to be made invisible because the change in shape in going from (b) to (c) is not observed. The solution comes with the realization that the shape of the crystal can be altered without changing its crystal structure by using lattice-invariant deformations (twinning or slip). All of the anomalies fall into place, including the irrationality of the crystallographic indices and orientations. The theory predicts the substructure of twins in martensite, later to be verified by Nishiyama & Shimizu (1959). Kenji Shimizu was another admirer of Jack's and visited him regularly in Oxford and at international meetings.

Jack did this rationalization of theories on several occasions during his life. With Bilby (7, 14), he showed that the surface dislocation analysis of interfaces could be compared with the crystallographic theory of martensite. Similarly, when W. Bollman produced the O-lattice theory (Bollman 1967), Jack showed that it was essentially a quantized version of the surface dislocation treatments by Bullough & Bilby (1956). The closure failure of the circuit that is used to define the Burgers vector of a dislocation could be generalized, using the surface dislocation concept, to interfaces between dissimilar crystals (33).

Jack's work and his review articles, which were famous for their depth, had a profound influence on the theory of interfaces in the solid state. He highlighted the ambiguities that exist in the deconvolution of equations into the structure in interfaces at a time when high-resolution transmission electron microscopy was hampered by badly interpreted images of interfaces.

The meaning and character of steps in interfaces became unclear, and Jack did a lot to clarify the confusion and explain the consequences of interface motion on the atomic mechanism of transformation. His 1982 R. F. Mehl Award lecture and paper on deformation by moving interfaces (35) is a wonderful and typically concise assessment of why interface structure matters in phenomena ranging from elastic twinning to rubber-like effects in metals.

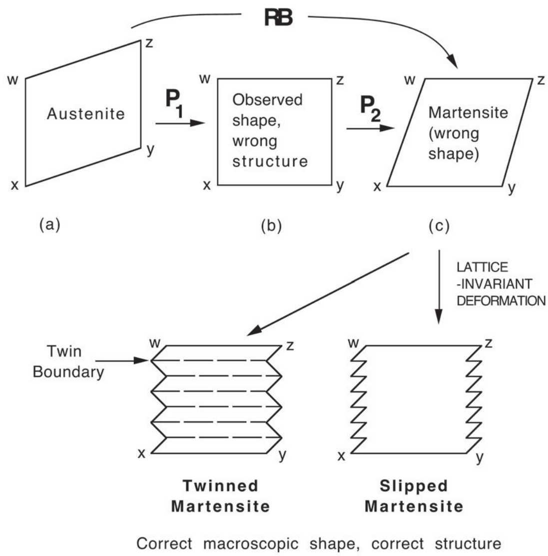

Figure 2. The essential features of the phenomenological theory of martensite crystallography (Bhadeshia 2001). (Adapted from (7).)

His knack for making precise statements where clarity is lacking is particularly prominent in that paper:

> In my personal opinion, the utility of the concept of closely-spaced coherency dislocations [steps] is confined to the calculation of stress-fields. … It seems useful to regard them as separate defects only when they are widely spaced along an interface plane which is effectively a stepped sequence of close-packed planes.

It is unfortunate that the contents of the paper were not fully understood by many, so Jack felt the need to write another paper in 1990 in which he stated that the conclusions were not new but had not been well recognized (47). He emphasized there the role of coherent *small* steps as opposed to the so-called *superledges*, which, in the context of displacive transformation, are 'extremely improbable'. There is another disarming statement, obvious to those involved in the theory of martensite but not to others, that 'models of the interface as a single array of intrinsic dislocations are not possible … if the close-packed planes of the two structures [austenite and ferrite] are regarded as exactly parallel'. And yet there are numerous publications today that continue to violate this fundamental outcome in considering interface structures. The two-dimensional matching of parallel planes is almost a disease in modern literature, and the fact that a particle is a three-dimensionally enclosed object is also neglected. Jack frequently pointed out that theory requires semi-coherence to be maintained on all interfaces of a particle, so it is unreasonable to talk of an incoherent patch on a ledge that moves on a semi-coherent plane when the transformation produces an appropriate shape deformation.

The story of superledges in displacive transformations did not end with the 1990 paper. He was invited to participate in a select conference in 1992, with the purported aim of resolving the confusion in the mechanisms of transformation. The resulting paper (48), published in 1994, exposes the sense of irritation that he must have felt. The paper begins by saying, 'Many

controversies in this field reflect linguistic rather than scientific difficulties.' But the paper is nevertheless thrilling to read, peppered with what he calls 'dogmatic statements' and 'rather obvious but important conclusions'.

Some of the discussion of superledges was associated with a raging controversy on a structure known as *bainite*, which occurs in steel just before the onset of martensitic transformation. The arguments were about the atomic mechanism, and whether this involves diffusion or is akin to diffusionless transformation as martensite is. With Edmonds, Jack wrote a scholarly review on the subject, published in 1984 (37), which was vehemently attacked by H. I. Aaronson and W. T. Reynolds Jr., leading to a series of exchanges between 1988 and 1989 in *Scripta Metallurgica* (39, 40, 44). Some of the criticisms did not represent the best codes of conduct associated with scientific discussion. So when invited again to write about bainite with Bhadeshia, he was reluctant, explaining that he was 'tired with bainite'. He was nevertheless persuaded, resulting in a 30-page article in *Metallurgical Transactions*, one that places bainite in the context of the myriad other transformations that occur in steels (46).

Jack's last word on bainite is in the third edition of *Theory of transformations in metals and alloys*, which appeared in print after he died (50). He presents a fair picture of the subject but does not mince his words: 'There are several objections to the Aaronson model; for example, it does not seem to take account of the lack of any solute atom mobility at the temperatures of bainite formation.'

It is worth mentioning a short article that Jack wrote in 1962 on the origin of surface relief effects in phase transformations, which precedes the bainite controversies but has considerable relevance in the interpretation of the displacements caused when atoms move in a disciplined manner (15). It is not commonly realized that this was the first paper to propose that the surface relief caused by a phase transformation need not be influenced by interstitial atoms. In other words, the transformation may in all crystallographic respects seem as if it is martensitic but may involve the uncoordinated motion (diffusion) of interstitial atoms such as carbon. One could therefore have a displacive transformation whose rate is controlled by the partitioning of carbon atoms between the parent and product phases. In steels, this is the Widmanstätten ferrite reaction; many years later, Bowles *et al.* (1977) demonstrated vividly that vanadium hydride formation occurs by this mechanism.

F. C. (later Sir Charles) Frank FRS had originally classified solid-state transformations as civilian (uncoordinated movement of atoms or reconstructive) and military (disciplined transfer of atoms or displacive) (Frank 1963). Jack liked this analogy and referred to it in his articles. He added a paramilitary transformation to account for his proposal that whereas the large atoms (iron and substitutional solutes) are transferred across the interface in a disciplined manner, the interstitials are not. This analogy is repeated in many undergraduate courses on phase transformations throughout the world.

There is one area that Jack identified in the 1965 meeting 'Physical Properties of Martensite and Bainite', which is as yet unsolved (21). This is to do with the nature of the deformation that occurs when an epitaxially semi-coherent boundary moves (figure 3). When the boundary AB moves to its new position C′D′, the misfit dislocations must climb, and the shape of the transformed region is changed to ABC′D′ from ABFD. The net deformation is therefore an invariant-plane strain (a combination of shear and dilatation). The question then arises whether the diffusion that is needed for the misfit dislocations to climb is sufficient to anneal out the shear. It has been argued that this may not happen because the climb distance is much smaller than the distance through which matter would need to be transported parallel to the habit

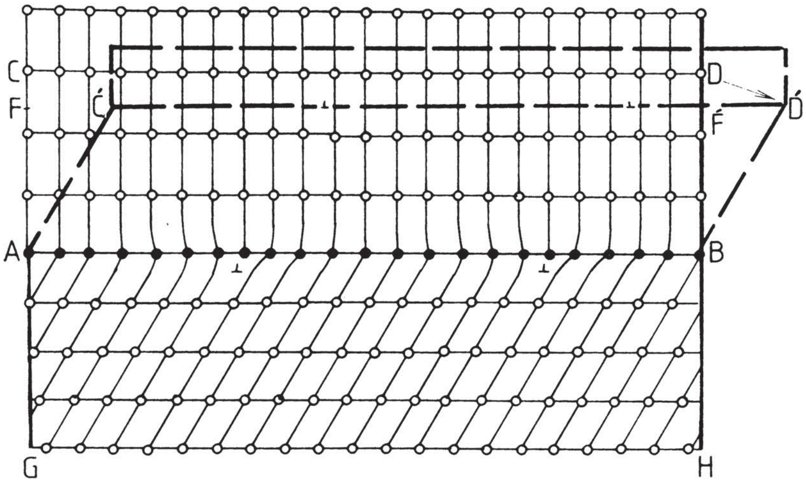

Figure 3. The shape change accompanying the motion of an epitaxially semi-coherent interface requires the climb of misfit dislocations with the help of diffusion. (From Bhadeshia (1982).)

plane. Christian thought this was a 'feeble' proposal and that a quantitative approach was long overdue. Work of this kind would also be relevant to his later proposal of a diffusional–displacive mechanism of transformation.

Jack was unusual in that he demonstrated a deep understanding of a very wide range of subjects; this permitted him to reach reasoned conclusions where others foundered. He made major contributions to the thermodynamics of martensitic transformations. When Eshelby (1957) came up with his elasticity theory dealing with the strains due to inclusions, Jack applied it in 1958 to calculate the strain energy due to an elastically accommodated plate of martensite (11). This was a unique contribution in that it predicted that the strain energy due to the dilatational component of strain should also depend on the aspect ratio of the plate. The resulting equation has had a profound effect on methods for estimating the transformation-start temperatures of displacive transformations.

During the early 1980s there was a deliberate effort to bring physicists into the growing field of martensitic transformations; this was productive and led to advances in the subject but also to some red herrings. Jack was one of those who could see the wood for the trees. He could see that it was difficult to convince solid-state physicists that there is any difficulty in nucleating martensite, whereas metallurgists could use classical nucleation theory to show that nucleation was impossible. Several papers were published by the physicists on the strain spinodal as a mechanism for the martensitic transformation. Jack once again pointed out the obvious, that we can see martensite and austenite coexisting, so there is very strong evidence that the parent lattice does not as a whole become mechanically unstable when martensite forms (34). But such an instability could arise locally, although if it does so, there would not be any essential difference with existing nucleation theory.

Research on the properties of body-centred cubic materials

The plastic deformation of metals and alloys with close-packed f.c.c. or hexagonal close packing crystal structures generally follows Schmid's law (Schmid & Boas 1928). Slip occurs by the sliding of close-packed planes in the direction of the densest atomic packing, and the plastic flow begins when the resolved shear stress on this slip system reaches a critical value. It was recognized at an early stage that the deformation of body-centred cubic (b.c.c.) iron did not conform to this law and that its behaviour could best be described in terms of pencil glide; that is, slip in a crystallographic direction (almost always <111>) but on a cylindrical, or at least non-planar, surface (Taylor & Elam 1926). Similar properties are also observed for other b.c.c. metals and alloys. Several common features are observed in their deformation behaviour, including a rapid increase in the yield and flow stresses with decreasing temperature, a marked sensitivity of the flow stress to the imposed strain rate, a sensitivity to small amounts of impurity or solute (particularly interstitials), and a tendency in many cases to brittle cleavage failure at low temperatures. It was first proposed by Heslop & Petch (1956) that the temperature dependence of the flow stress in b.c.c. iron may be due to a sizeable lattice friction stress, the Peierls–Nabarro force, but the reason for this behaviour was not understood.

It was in this context that Jack's interest in the deformation behaviour of b.c.c. materials began. In 1956, he spent some time working with his former student, Z. S. Basinski (FRS 1980), at the National Research Council laboratory in Ottawa. Jack described the seminal nature of this experience as follows:

> In 1956, I spent six months in Ottawa, in Dr. D. C. K. McDonald's research group working partly with Basinski and partly with Dr. W. B. Pearson, both of whom had migrated there from Oxford a few months earlier. This was a very active research group and, especially from Basinski, I learned much about plastic deformation of metals and new methods of testing for thermally activated processes by changing the strain rate suddenly during a conventional mechanical test. I was his co-worker or research assistant! When I returned to Oxford, I started research as soon as possible on continuing this work and this led to my second major research interest in the mechanical properties of b.c.c. metals such as niobium, tantalum and molybdenum, as well as the more familiar iron. This work led to Hirsch's concept of the screw dislocation being responsible for the high values of the Peierls–Nabarro stress which was a logical deduction from our work. Subsequent research by computer simulation into the core structure of dislocations and later of interphase boundaries followed and is still very important.

The key advance made by Basinski and Christian was to explore the effects of changing the strain rate while keeping the specimen temperature constant. Cottrell & Stokes (1955) had previously introduced a test procedure in which deformation was established at one temperature, stopped, and then resumed at a lower temperature. This enabled the thermal component of the stress at constant dislocation structure to be evaluated. Basinski (1959) had used that procedure to study the nature of the barriers to dislocation movement in f.c.c. metals during the process of work hardening. However, the Cottrell–Stokes method was tedious because the process of changing the specimen temperature was slow. In an important paper published in the *Australian Journal of Physics* (13), Basinski and Christian used both temperature and strain rate change methods to show definitively that the strength of pure iron at low temperatures was controlled by the Peierls–Nabarro force, and that thermal activation was the key process for dislocation glide.

On his return to the UK, Jack initiated the building of equipment for growing single crystals and special machines for performing mechanical testing at low temperatures. This led to major research activity at Oxford during the next 20 years on the deformation behaviour of single crystals of the b.c.c. metals. In an epic series of papers on this very complex subject, Jack and his students and co-workers reported elegant and comprehensive studies, which included work on a range of pure metals (17–20, 24–27) plus substitutional (29, 31, 38) and interstitial (45) solid solutions, and particle-strengthened materials (42, 43). Highlights included a 1964 paper with Brian Masters, which contained the definitive formulation of the thermodynamic treatment of thermally activated glide in b.c.c. crystals with the use of the stress-dependent activation energy (19). Another landmark was the first paper with Glyn Taylor on the high-temperature, ultra-high vacuum annealing of niobium single crystals (20). This led the way in studies of b.c.c. refractory metal crystals by eliminating the yield point, and led to the discovery of anomalous slip. These definitive and frequently cited papers established him as a leading international authority in his second major area of research. Much of this work was reviewed in his Campbell Memorial Lecture in 1982 (36).

From the work at Oxford and elsewhere, it became clear that there was asymmetry of slip for glide on the {211} planes, with shear in the twinning direction being easier than the reverse. The realization of the crucial role of screw dislocations in this behaviour emerged only slowly, with contributions from several research groups and several experimental techniques, notably etch pitting studies, observations of slip line traces and (most importantly of all) transmission electron microscopy, which showed directly the existence of extended screw dislocation segments in deformed b.c.c. metals. Hirsch (1960) first emphasized that a screw dislocation lies along a three-fold symmetry axis of the b.c.c. structure so that the atomic structure of its core is non-planar and three-dimensional, and that this could make the dislocation relatively difficult to displace at low temperatures, and also make its directional behaviour asymmetric. This led to much theoretical work on the nature of the core structure of dislocations in b.c.c. metals. This showed that there was a convergence between the dislocation dissociation model and the core friction stress model, for the limiting case of small rearrangements of the atoms at the dislocation core. A fuller review of thermally activated deformation of b.c.c. metals and alloys has been provided by Glyn Taylor (Taylor 1992), Jack's principal co-worker in this field. A definitive account of computer modeling studies of dislocation core structures in b.c.c. materials has been given by Vasek Vitek (Vitek 1992). Taken together, the experimental and theoretical work in this area transformed our understanding of the fundamental behaviour of a most important class of engineering materials.

Other research interests

The subject of stacking faults and twins represented another strand of Jack's research interests. To some extent this formed a link between his work on martensitic transformations and that on b.c.c. metals. In his early research, he developed improved experimental methods for the estimation of the density of stacking faults in a material from detailed analysis of X-ray diffraction data (4, 10, 12). He wrote, jointly with Peter Swann, a major review article on stacking faults in metals (22), and another much-cited and authoritative review with Vitek, covering both dislocations and stacking faults (30). He became interested in the nature of the coordinated atomic movements that take place during mechanical twinning, which are very

closely related to those that take place during martensitic transformations, and he explored the very similar behaviour of twinning dislocations and transformation dislocations (28). He also explored the relation between the twinning processes that occur during phase transformations and those that occur under mechanical loading. He published an important paper with David Laughlin on deformation twinning in superlattice structures derived from disordered b.c.c. or f.c.c. solid solutions (41). Later, with Subhash Mahajan, he produced a definitive review of the whole field of deformation twinning (49). This quickly became his most cited single publication, apart from his major treatise on phase transformations, which is discussed in more detail below.

The theory of transformations in metals and alloys

The origin of this monumental work dates back to at least 1956. Jack wrote an editorial review of the conference on phase transformations that had been held that year, in which he noted the inadequacy of existing systems for the classification of phase transformations and for the definition of the characteristics of specific types of reactions, particularly those that involved a shape change. He subsequently played a leading part in the development of an improved system of classification, which involved careful distinctions between homogeneous and heterogeneous reactions, homogeneous and heterogeneous nucleation, thermally activated and athermal growth processes, interface-controlled and diffusion-controlled growth, and between continuous and discontinuous reaction processes (16). The final version of the diagram setting out his classification of transformations according to growth processes is reproduced as figure 4.

His book covered all of the major transformation processes in a comprehensive manner and contained much additional material. In particular, he presented formal treatments of the geometry of crystal lattices and crystal interfaces, point and line defects in crystals, diffusion in the solid state, and the mechanism of mechanical twinning. A common theme running through the book is the underlying unity between different but related phenomena. His encyclopaedic knowledge meant that he was able to identify links and connections that others had missed.

Jack laboured on his book for many years, often working on it at home, late into the night, after a full day in the department. It was not unknown for him to try out sections of the draft on his third-year undergraduate pupils, who sometimes found that, instead of a reading list for the next tutorial, they were presented with a pile of carbon-copied manuscript pages to digest. He put the finishing touches to it during a sabbatical spent at Case Institute of Technology during the academic year 1962/63, and the first edition was eventually published in 1965 (23). An insightful review by C. R. Tottle, published in *Nature* (Tottle 1966), is worthy of reproduction:

> Dr. Christian has produced a magnificent work of scholarship which must have occupied many years of investigation. [The book] is at once, at an advanced level, both a text-book for those interested in transformations, and a reference book for a wide range of research workers. The approach is totally different from those of past authors. Classification and definition of transformations occupy a chapter, since the author includes many solid-state changes and not only phase reactions. His preface claims, quite rightly, to include 'every major kinetic effect in physical metallurgy and solid state physics, with the notable exception of deformation by slip'. Twinning is included, and lattice defects, since they are involved in martensitic transformations and diffusion. … Undergraduates in honours schools should be capable of coping with the text, but graduate students are likely to be the main readers. … Already my colleagues are devouring it.

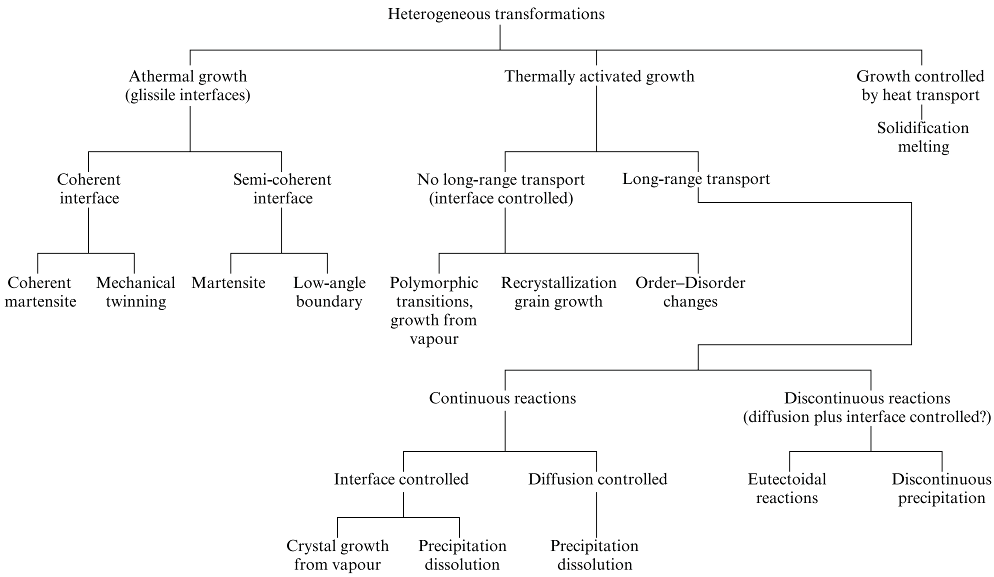

Figure 4. Jack Christian's comprehensive scheme for the classification of phase transformations according to growth processes. (Redrawn from (32), courtesy of Elsevier Science Ltd.)

Jack soon began working on a second edition, in two volumes, but progressively worsening health made this a difficult task. Part I of the second edition, covering the general theory, was published as a stand-alone volume in 1975 (32). For many years he was unable to complete Part II, covering specific types of transformations, but finally, by a Herculean effort, he finished this task late in 2000, shortly before his death. The third edition, in two volumes, and consisting of a revised version of Part I, plus the newly completed Part II, was published posthumously in 2002 (50).

It is no exaggeration to state that this classic treatise had a profound influence on a whole generation of materials scientists all over the world. For the first time it provided a rigorous and comprehensive treatment of the theory of the phase transformations that occur in metals and alloys, as well as in many other materials. It was, quite literally, a masterpiece. It helped to establish the subject of physical metallurgy as an intellectual discipline in its own right, and set the standard for graduate teaching in the subject for two generations. At the time of writing this memoir, the various editions of the book have attracted nearly 4000 citations in the scientific literature of the subject.

Personal life and health

In 1949 Jack married Maureen Lena Smith, only daughter of William and Hilda Smith (*née* Dumighan) at Billingham, County Durham. It was a very happy marriage, and they supported each other throughout their busy lives. They both loved the arts and were regular theatre and cinema-goers. Maureen graduated (in English) from Durham University. After marriage, she took a Diploma in Education at Oxford and taught for many years at various schools

in Oxford. They had three children, Louise Hilda (born in 1952), who is a very successful solicitor, specializing in human rights cases, John William (1953), who is a data-processing expert, and Timothy James (1966), who, sad to relate, predeceased Jack in 1999.

Maureen recalled one of the consequences of being married to a dedicated scientist:

> When we were first married, I was a graduate student and Jack and Bill Pearson were doing some experimental work in two rooms which were each side of the Natural History Museum. This involved a certain amount of trekking through the Museum with a torch at 2 or 3 in the morning. I still remember the moon shining onto the dinosaur and it being a very eerie place to be. There was a cage of locusts which sprang into life as the torch illuminated that part of the museum. Jack always insisted that I accompanied them on these late nights.

In the late 1970s Jack began to develop Parkinson's disease. For the rest of his life he fought this affliction with courage and fortitude, and refused to allow it to affect his work or his social life. As his physical condition deteriorated, his handwriting became indecipherable and his speech difficult to follow. But his mind remained sharp and clear, and he became skilled in the use of a word processor; this enabled him to maintain his intellectual output and his communication with friends and colleagues. In 1995 he underwent a delicate brain operation (pallidotomy), which greatly improved the control of his movements. It was this that enabled him to undertake the mammoth task of completing the third edition of his book.

Jack described his main outside interests as being theatre-going, reading, gardening, watching cricket, and foreign travel. He was also very keen on hill walking, particularly in his native Yorkshire, but increasing infirmity due to Parkinson's disease rendered this impracticable in later years. He was an avid reader and enjoyed the major classics as well as contemporary work, both fiction and non-fiction. Music was less important to him. He professed an inability to sing in tune, but he enjoyed listening to the music of composers ranging from Mozart and Beethoven to Cole Porter, George Gershwin and Glenn Miller.

In 1987 Maureen was elected as Labour Councillor to represent Marston Ward on Oxford City Council, and she served successively as Chair of the Estates and Planning Committees of the Council before being elected Lord Mayor of Oxford in 2000. Jack was immensely proud of Maureen's political achievements, and in spite of his physical disability he escorted her to many of her official functions. On 26 February 2001 he accompanied her at the ceremony in the Town Hall at which Colin Dexter (author of the 'Inspector Morse' books) was given the freedom of the City of Oxford, and he enjoyed meeting members of the cast at the reception afterwards. Less than 24 hours later, he died suddenly, in the department where he had spent his working life.

Research collaborators, and recollections of colleagues

Jack's qualities as a research supervisor were described vividly by Dr Glyn Taylor and Professor Keith Bowen FRS, both of whom conducted their doctoral research under his supervision (Taylor & Bowen 2001):

> Jack (known as 'Chris' to his students) believed in describing research projects in broad terms, so students were obliged to work out their own inclinations. He was also kind to his students. On one occasion, in the days of mechanical typewriters and rigid submission dates, Jack, on hearing that one of his students was having difficulty finding a typist to do the thesis, offered his services with the words, 'I'm two-fingered, fast, not very accurate, but I don't charge.' One student claims

that Jack never answered a question directly in eight years of undergraduate, postgraduate and postdoctoral supervision. Instead came the dreaded words, 'Well, what do you think?' The ensuing discussion not only solved the problem but developed intellectual powers far more than any direct answer could have done.

Another characteristic of Jack's, both as a tutor and research supervisor, was that his office door was always, quite literally, open. Anyone from the most senior professor to the most junior graduate student could simply walk in and be assured of a warm and unassuming welcome. He was a constant source of advice and inspiration to students and colleagues from all over the world. He often went to extraordinary lengths to be helpful, for example by agreeing to read the manuscripts of major papers by colleagues before their submission for publication, and providing detailed (and sometimes devastating) critiques, without any thought of formal acknowledgement in the final printed version.

Jack developed lasting friendships and scientific collaborations with many of the world's most distinguished materials scientists. He was always generous in describing his interactions with his collaborators. Here are a few typical comments of his (lightly edited):

> First and foremost is Professor Basinski. He was my first real research student and it was frequently difficult to know who was the supervisor and who the student. Bill Pearson was a tireless and brilliant researcher with an enormous capacity for hard work over very long hours. … Bruce Bilby was probably the cleverest scientist with whom I worked directly, but our paths diverged when he became interested in fracture. … In the USA I should mention Professor Morris Cohen of M.I.T. [Massachusetts Institute of Technology] who has been a dear friend for many years and still pursued science well into his eighties and Dr. John Cahn who has put me right on so many issues over the years. I have been fortunate to work for limited periods in many laboratories in the USA … and in all of them I have made dear friends who have helped me with my research. Similarly I have many friends whom I have first met at conferences around the world, and like most scientists I have much appreciated the opportunities for travel … The meeting of international workers in a particular field can lead to firm friendships and I have been extremely fortunate in that respect. … I must mention all my research students who did the hard work and over the years have influenced me in many ways; most of them still keep in touch. Finally, a large influence on my life at Oxford was Professor Hume-Rothery who started me on my particular career; he was a true gentleman and friend.

Jack's colleagues and friends were generous in their tributes to him. Their recollections often reflected his personal qualities.

Sir Peter Hirsch FRS writes:

> Jack was a most modest and unassuming man, of utter integrity and high moral principles. In discussions he was more than fair to those who held views differing from his own, but he also never failed to expose weak points in any argument. Flaws in a scientific argument were often exposed by the innocent question, 'are we talking about the same thing?' He combined a capacity for hard work with a sense of humour and an exceptional critical faculty. He was warm and generous in his relationship with others and he was the nicest of colleagues; he had only friends and no enemies—no one ever said an unkind word about him.

Dr Thomas L. Altshuler writes:

> It was so refreshing and wonderful to have a professor so welcoming and caring about the well-being of his students.

Professor Robert Pond writes:

> He was simultaneously critical and encouraging, with a lot of gentle humour thrown in. He had special expressions: 'I don't disagree with anything you say'—meaning 'OK, but there's nothing

new here', or, if he liked something, 'now that is cunning.' One day I said how unlucky he'd been with his health; he dismissed this idea summarily, 'oh no, these days some people get really terrible things.' Jack had very special personal and intellectual qualities.

Rev. H. E. J. Cowdrey DD FBA, St Edmund Hall, Oxford, writes:

His uncomplaining acceptance of his illness was quietly inspirational. Here, of course, so much was owing to Maureen, whom he supported both in her eminent civic career and in personal sorrow. It was a wonderfully mutual relationship, as was illustrated by a remark of Maureen's when a comment was passed on her support for Jack: 'People say that, but it has been as nothing as compared with his support for me.'

Postscript

A poignant reminder of the changed atmosphere surrounding fundamental science in the UK came during the run-up to the 2001 Research Assessment Exercise. Shortly before his death, Jack was included in the first draft of the submission from the Oxford Department of Materials because, although officially long retired, he continued to be active in research. However, a telephone call soon came back from the central university administration: 'Who is this person Christian who you want to put in your submission? He only has three outputs in the period of interest. Don't you think you should leave him out?' Efforts were made to explain to the administrator concerned that it was the quality of the scientific contributions that mattered, not merely the number. Jack, himself, said that he was glad that he had lived and worked when he did, and expressed grave doubts as to whether he would have been able to succeed in the same way in the modern era. He was not bound by metrics, either in terms of success in obtaining research funding, or numbers of publications, or citation indexes. Instead, he was motivated by a passionate desire to know the truth, and he used all of his formidable intellectual powers to strive towards that end. His curiosity-driven research led to a series of landmark achievements that changed the way in which we think about the phase-transformation behaviour and mechanical properties of metals and alloys.

Honours, awards and appointments

From the 1950s onwards, Jack's growing international reputation brought him many invitations to conferences and research laboratories. He held visiting appointments at several universities and institutions in the USA and Canada, including Case Institute of Technology, the University of Illinois, MIT, Stanford University, the University of Virginia, the National Research Council Laboratory in Ottawa, and the National Bureau of Standards in Washington. He was also active as an editor and reviewer for major international scientific publications. He served as Editor or Senior Editor for several journals, including *Acta Metallurgica*, *Progress in Materials Science*, *Journal of the Less-Common Metals*, and *Physics of Metals and Metallography*, assignments that he performed with his usual meticulous thoroughness and tact.

He gave several named lectures, including the ASM Hume Rothery Memorial Lecture (1976), the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME)

Institute of Metals Lecture (1981) and the ASM Edward de Mille Campbell Memorial Lecture (1982). He became a Fellow of the Institute of Physics and of the Institution of Metallurgists, and was elected to the Fellowship of the Royal Society in 1975. He received the Rosenhain Medal of the Institute of Metals in 1968, the Robert Franklin Mehl Award of AIME in 1981, the Platinum Medal of the Metals Society in 1984, the *Acta Metallurgica* Gold Medal also in 1984, the University of Pennsylvania Medal for Distinguished Achievement in 1996, and the Gold Medal of the Japan Institute of Metals in 1999. A full list of his appointments and awards is given below.

Degrees

1946	BA (Physics), University of Oxford
1949	DPhil, University of Oxford
1950	MA, University of Oxford

Appointments

1944–45	Honorary Scholar, The Queen's College, University of Oxford
1945–48	Research Assistant, Inorganic Chemistry Laboratory, University of Oxford
1948–51	Departmental Demonstrator in Metallography, Inorganic Chemistry Laboratory, University of Oxford
1951–55	Pressed Steel Company Research Fellow, University of Oxford
1955–58	University Lecturer in Metallurgy, University of Oxford
1958–67	George Kelley Reader in Metallurgy, University of Oxford
1963–88	Professorial Fellow of St. Edmund Hall, Oxford
1967–88	Professor of Physical Metallurgy, University of Oxford
1987	Honorary Professor, Beijing University of Iron and Steel Technology
1988–2001	Emeritus Professor of Physical Metallurgy, University of Oxford
1988–93	Senior Research Fellow, St Edmund Hall, Oxford
1993–2001	Emeritus Fellow, St Edmund Hall, Oxford

Honours and awards

Prizes and medals

1968	Rosenhain Medal, Institute of Metals, UK
1981	Robert Franklin Mehl Award, American Institute of Mechanical Engineers
1984	Platinum Medal, The Metals Society, UK
	Acta Metallurgica Gold Medal
1996	University of Pennsylvania Medal for Distinguished Achievement
1999	Gold Medal of the Japan Institute of Metals

Membership of academies and learned societies

1962	Fellow of the Institute of Physics
	Fellow of the Institution of Metallurgists
1975	Fellow of the Royal Society
1991	Honorary Member, Indian Materials Society
	Honorary Member, Japan Institute of Metals

Named lectures

1971	Robert S. Williams Lectures, MIT
1976	Hume Rothery Memorial Lecture, American Society for Metals
1981	Institute of Metals Lecture, TMS—American Institute of Mechanical Engineers
1982	Edward de Mille Campbell Memorial Lecture, American Society for Metals

Visiting appointments

1956	Visiting Scientist, National Research Council, Ottawa, Canada
1959	Visiting Professor, University of Illinois
1962–63	Distinguished Visiting Professor, Case Institute of Technology, Cleveland, Ohio
1963	Visiting Professor, University of Illinois
1971	Visiting Professor, MIT
1972	Visiting Professor, University of Virginia
	Visiting Professor, Stanford University
1979	Visiting Scientist, National Bureau of Standards, Washington DC

Editorships

1962–64	Editor, *Structure Reports (Metals)*
1967–73	Associate Editor, *Acta Metallurgica*
1970–2001	Senior Editor, *Progress in Materials Science*
1974–91	Translation Editor, *Physics of Metals and Metallography*
1976–85	Editor-in-Chief, *Journal of the Less-Common Metals*

Acknowledgements

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