BIOGRAPHICAL
MEMOIRS

Bruce Alexander Bilby. 3 September 1922 –– 20 November 2013

G. W. Greenwood

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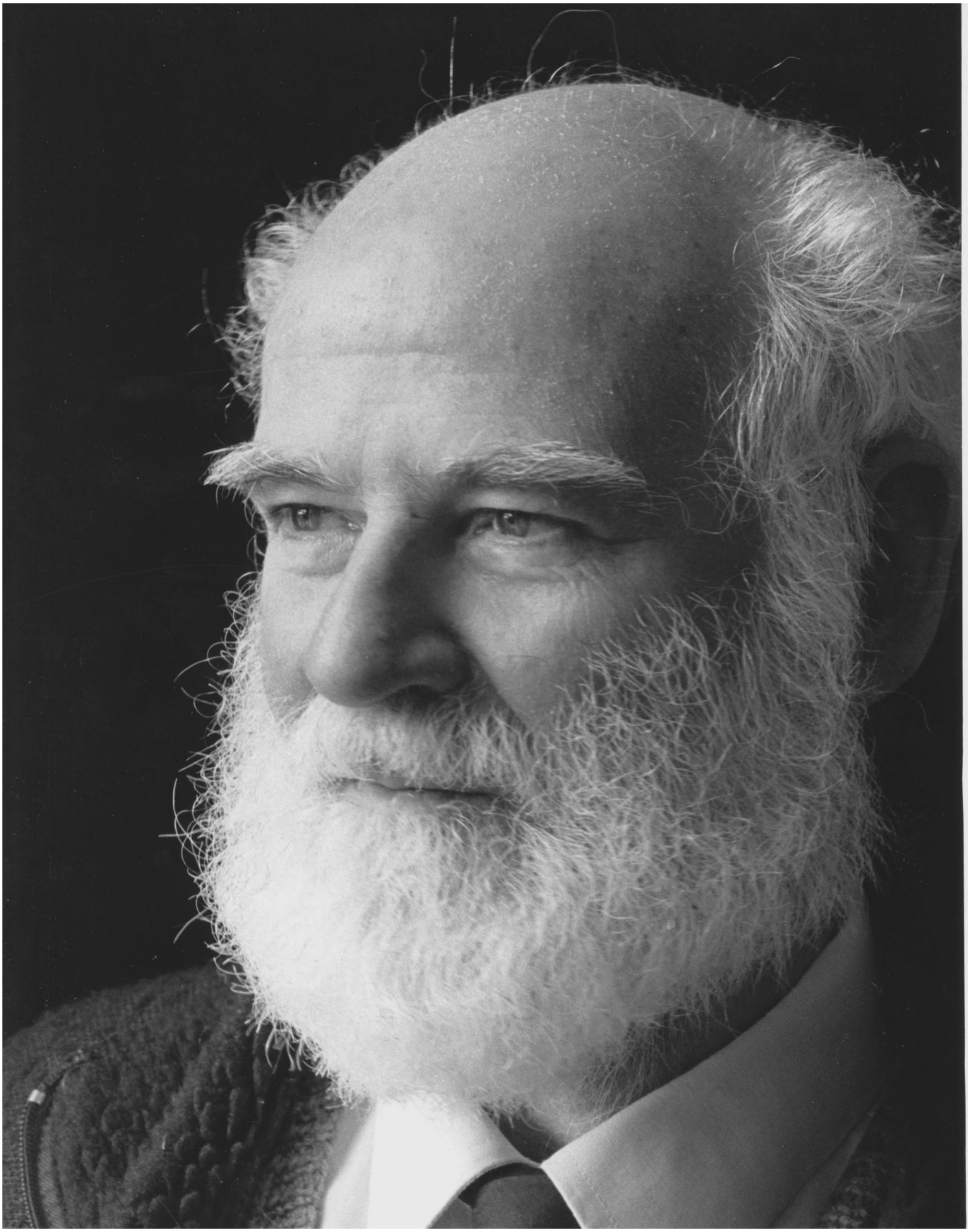

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Elected FRS 1977

By G. W. Greenwood FRS FREng

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Emeritus Professor Bruce Bilby, who died in November 2013 at the age of 91 years, was among the few pioneers who made great contributions to the understanding of crystal defects, notably of dislocations, in providing precise geometrical descriptions of their form, arrangement, interaction and movement. This has led to a clear and experimentally verifiable interpretation of phenomena that include the occurrence of yield points, strain ageing, mechanisms of twinning and martensitic transformations, and the characteristics of atomic separation that lead to fracture. Bruce's approach often made use of areas of pure mathematics, whose relevance had not previously been suspected, in elegant descriptions of defected crystal structures. Much of his work is related to the role of defects in metals and alloys in their influence on mechanical properties. It assists in considerations of safety assurance of large structures. It links macroscopic behaviour with phenomena on an atomic scale and has underpinned technological judgements.

Early years, education and war service

Bruce was born in Edmonton, London, the eldest of three children. His father, George, had entered the Civil Service by taking the examination for boy clerks and was employed as an Officer of Customs and Excise. George had once hoped to become a government chemist and maintained a keen amateur interest in chemistry. He also built primitive crystal radio receivers and erected a tall mast in his garden to assist in wireless reception. Bruce's mother, Jean (*née* Telfer), was a shorthand typist before marriage and had first met George at a cycling club. They became keen gardeners and kept chickens. In winter they enjoyed skating when a nearby lake was frozen and in summer extended their travels to the countryside in an old Austin Seven. Bruce inherited many of the interests and practical abilities of his parents.

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When Bruce was 10 years old the family moved to Dover, where he attended the Dover County (later Grammar) School for Boys. New interests arose there, especially in the sea and ships, which were to become an abiding fascination. He particularly valued a huge, though obsolete, copy of *Lloyds register of shipping*, handed down by a relative, which added to his interest in 'ship spotting'. Bruce liked to construct various objects and machines with his Meccano set but also enjoyed energetic pursuits, including cycling, roller skating and table tennis. He excelled at swimming, later winning his school's cup and playing water polo for the Dover Swimming Club. During his school days Bruce made extensive use of his small Hercules cycle, which had no gears. After various local expeditions, he prepared himself for longer journeys with several rides to Chatham and back, a round trip of some 80 miles, before riding to Westcliff-on-sea via the Gravesend ferry to visit his cousins. With thoughts of war approaching and the anticipation of shortages, his parents bought him a full size Rudge–Whitworth machine with Sturmey–Archer three-speed gear. This cycle was later to carry him several times between Cambridge, South Wales and South Devon when he was a university student.

At school his fascination with chemistry was gradually overshadowed by physics and mathematics, largely through the inspirational physics teaching of the senior physics master, W. E. Pearce. The start of the war had initially little influence on the pattern of life, but this changed suddenly. At one week's notice in June 1940 the Dover schools were evacuated. Bruce's school was relocated in Ebbw Vale with a substantially different environment from that which was previously familiar. Nevertheless, Bruce adapted to the changes and the school did all that was possible to provide continuity. There were some interesting and memorable new experiences. One of these was a visit to the South Wales steelworks of Richard Thomas and Baldwin, in which the huge industrial scale of operations involved in the melting, casting and mechanical working of steel made a lasting impression.

Bruce was awarded a state scholarship on the results of his Higher School Certificate Examination, but he took advice to remain at school for a further term and sit the Open Scholarship Examinations in natural sciences at Cambridge in December 1940. His decision was partly influenced by the example of J. W. (later Sir James) Menter (FRS 1966), who had taken similar advice in the previous year. Bruce was successful in being awarded an Open Minor Scholarship within the Peterhouse group of colleges. Because of wartime conditions, he was able to start immediately at the university and, supported by his college scholarship, he entered Peterhouse in January 1941.

He had very much looked forward to studying physics at university level, but was aware that, within the Part 1 Natural Sciences Tripos, additional subjects must be chosen. A decision was not easy when he noted, with some apprehension, that a course on mineralogy was unavoidable in his preferred combination. Surprisingly, in the presentation of this subject, he found its emphasis on crystallographic aspects and on x-ray diffraction much more to his liking than he had expected. With the excellent treatment of crystallography, the course was to have decisive influence on his future career. He completed Part 1 of the Tripos in June 1942 with a college prize and Andrew Perne Senior Scholarship. He went on to take Part 2 in Physics, finishing his degree course in June 1943.

In parallel with academic studies, the nation's state of war required additional commitments, and Bruce served in the Signals Section of the University Senior Training Corps. Previous experience in his school's Cadet Corps, where he had risen to the rank of corporal, helped in his adaptation. Subsequently he joined the Home Guard and this required him to do some work on the land during vacations as an agricultural labourer, assisting in food production to meet the country's wartime needs. With his strong physique, one of his allocated tasks was to assist in wheat threshing by throwing sheaves to the top of the machine with a pitchfork. Very tired towards the end of the day, he failed to release the pitchfork from one of the sheaves and both were swept together into the machine. Fortunately, despite a loud rasping and the emergence of wood splinters and tangled metal from the exit port, the machine was largely undamaged. That was the last time this activity was included in his agricultural work! Back at the university, a totally contrasting duty was to spend long nights on college roofs undertaking fire-watching duty.

After his completion of Part 2 Physics, Bruce was interviewed by the Central Register Committee set up in wartime to allocate the employment of scientists graduating at that time. He was recruited into the Radiography Section of the Naval Construction Department of the Admiralty formed under the initiative of the Superintendent of Welding Development. There were brief induction periods for training, which involved works experience in the Royal Dockyards at Portsmouth and Chatham, Woolwich Arsenal, Kent Alloys and the X-ray Department of Bristol General Hospital, and attendance in London at the Kodak School of Industrial and Engineering Radiography. Work in dockyards provided valuable experience of industrial conditions. Bruce was commissioned as Lieutenant (Sp) in the Royal Naval Volunteer Reserve and sent to Germany immediately after the war had ended to investigate what might be learned from corresponding work and equipment in the former enemy country. After completing the required period of three years' Admiralty Service he was free to leave.

Birmingham

In 1946 Bruce took up a new post as a Science Research Council Research Assistant in the Department of Metallurgy at the University of Birmingham. The department had a distinguished record, extending over several decades, in its contributions to metallurgical practice. Its head, Professor D. Hanson, was keen to introduce and build on many of the impressive new concepts currently emerging from studies in metal science. Bruce endorsed such an approach and was ready for further changes in his life. At this time he married his first wife, Hazel Casken, a radiographer who had worked in the firm of David Brown at Penistone, South Yorkshire. They had met three years previously while on the course at the Kodak School of Radiography they both attended.

At the university, Bruce joined the team led by A. H. (later Sir Alan) Cottrell (FRS 1955) with interests centred on plasticity and the strength of metals and alloys. After a year of experimental work, involving the construction of an extensometer and a furnace for growing single crystals, Bruce moved on to study dislocation theory and its possible implications. At that time very few people were interested in the concept of dislocations: there was no direct experimental evidence for their existence and there had been few publications in the field. Studies in this area were, however, beginning at several places in the USA, Japan and Germany, but particularly in the UK with groups working under Ergon Orowan (FRS 1947) at Cambridge and in the Department of Physics at Bristol University, under N. F. (later Sir Nevill) Mott FRS, that included F. C. (later Sir Charles) Frank (FRS 1954), F. R. N. Nabarro (FRS 1971) and J. F. Nye (FRS 1976). The Department of Metallurgy at Birmingham developed close links with physicists at Bristol.

Bruce's initial interest was in Cottrell's theory of the elastic interaction of solute atoms with dislocations to explain yield point phenomena and strain ageing in steels containing small amounts of carbon or nitrogen. Experimental evidence had shown that the yield point could be removed by small amounts of plastic deformation but it would return after the steel was aged for a time depending on temperature. Bruce deduced (1)* that, after dislocation/solute separation caused by the plastic deformation, the yield point would return depending on the time raised to the power 2/3. This agreed with experimental results on several systems as well as carbon or nitrogen in iron, for which the effect was strongest. As a related effect, it was also known that carbon and nitrogen could diffuse sufficiently rapidly at about 200 °C in iron for this to occur during plastic deformation. The stress–strain curves would then show serrations and the ductility would be reduced (2). Cottrell had provided approximate values of the dislocation/solute interaction energy by an essentially intuitive approach. With Cottrell's encouragement, Bruce went to greater depth and, using the Rayleigh–Betti reciprocal theorem, was able to produce rigorous mathematical analysis (3).

At that time, many metallurgists were still sceptical about the reality of dislocations in the absence of more direct experimental evidence of their existence. Bruce gave lectures in different parts of the country to several regional branches of the Institute of Metals on the subject 'What is a dislocation?' One of the objectives was to familiarize those working in industry with the latest developments in the theory of the strength and plasticity of metals. The lectures were generally received with interest and enthusiasm, although they provoked some tongue-in-cheek reactions. One of these was from W. Hume-Rothery FRS, who commented 'a dislocation is an invention of a mathematician who cannot understand the properties of metals'. But the science moved on. Over the next three decades, P. B. (later Sir Peter) Hirsch (FRS 1963), Hume-Rothery's successor as Isaac Wolfson Professor of Metallurgy at Oxford, was a leading figure among those who provided direct and irrefutable evidence of the existence of dislocations and of their properties that verified mathematical predictions. They also went on to show that knowledge of the characteristics and behaviour of dislocations is important in the design, manufacture and performance of solid state electronic devices. Previously, Hume-Rothery had not been the only eminent scientist to doubt the value of dislocation concepts. His opinion was shared by several others, including E. N. da C. Andrade FRS, Quain Professor of Physics at University College London, who had provided, in his wide-ranging and well-respected experimental research, much new information on metal plasticity and creep but remained doubtful that dislocation theory would prove capable of providing viable explanations.

Aware of these views, prevalent in the mid twentieth century, and of the necessity of a wider understanding and appreciation of the potential importance of dislocations, Bruce recognized the need first for improved visualization of their geometrical character. To assist in this (4), through demonstrating the location of atomic positions, he created models from wooden balls connected by curtain wire by which three-dimensional aspects could be more widely understood. These creations made a strong impact for students and others in their understanding of crystal defects.

Such a model is illustrated in figure 1, although details in the photograph are far less easy to decipher than those provided by a complete all-round view of the actual object. The models were to prove especially valuable, even to those with relatively little mathematical experience, in the elucidation of screw dislocations and in the operation of Frank–Read sources

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

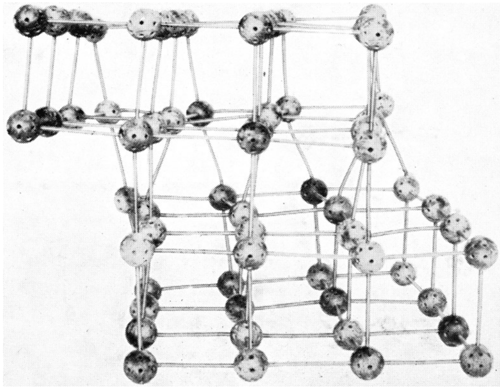

Figure 1. A wire-and-ball model of a crystal containing a screw dislocation. (From (4), with kind permission of the Institute of Metals.)

through which dislocations could be generated. Such visualization in three dimensions was essential to an understanding of the significant geometrical features. This led on to dynamical considerations, which could be demonstrated by systematic uncoupling and rejoining of wire and balls in new positions. The models were used extensively in lecture demonstrations, not only by Bruce but also by others including Sir Laurence Bragg FRS in a Royal Institution Lecture. A greatly enlarged photograph of a model of a crystal containing a crossed grid of screw dislocations was placed over the entrance to the Crystallography Section at the 1951 Festival of Britain Exhibition. Bruce realized that its selection was due to its decorative properties rather than its scientific revelation. Although he was pleased to have this recognition of the model's photographic qualities, he preferred to see more instructive examples of the models in use. Nevertheless, such examples found their way elsewhere and, for those with more mathematical appreciation, the demonstrations assisted in recognizing the importance of adopting vectorial representation (5), through which the significance and usefulness of the dislocation concept then became clearer. With agreed sign conventions, it was shown that displacements could be represented unambiguously by a single vector analogous to the vector that determines the direction of motion of a wire in relation to the electric current and magnetic field in a dynamo.

After five years at Birmingham, which included conferment of his PhD in 1949 and subsequently a University Research Fellowship there, Bruce moved to Sheffield in the autumn of 1951.

Sheffield

Bruce joined the Department of Metallurgy at Sheffield University to which, a year previously, A. G. Quarrell had been appointed Professor of Physical Metallurgy. Aided by industrial and government support supplemented by its own resources, the university was substantially expanding in this area. Simultaneously with Bruce's joining, the department was further reinforced by the arrival of Dr R. W. K. (later Sir Robert) Honeycombe (FRS 1981), G. B. Greenough, D. W. Wakeman and A. R. Entwisle.

Bruce's appointment was to the Royal Society Sorby Research Fellowship, and the University of Sheffield was to become the base for the remainder of his working life. On completion of the tenure of this post and, after a brief period as J. H. Andrew Research Fellow, he became a permanent member of the academic staff of the university. The title of Reader in Theoretical Metallurgy was conferred upon him in 1958 and this was followed by promotion to a personal chair in 1962.

Sheffield was delighted to have the opportunity, and now the basis, for the exploration of dislocation concepts with consideration of their promise in explaining much that had remained obscure. Bruce had brought his dislocation models with him, and their value was soon realized. This was reflected at a Christmas party, in a light-hearted way soon after his arrival, by research students in their adapting and ascribing to him the song 'When I was a lad' from Gilbert and Sullivan's operetta *HMS Pinafore*:

When I was a lad I was always a trier,
I used a lot of balls and curtain wire.
I fastened them up with the greatest glee
in complicated patterns like a Christmas tree.
Then I painted them red and I painted them yellow
and that's how I came to be a Sorby Fellow.

Dislocation theory at Sheffield

Bruce began work with his first research student, R. Bullough (FRS 1985), on aspects of mechanical twinning and of martensitic transformations, initially examining the hypothesis that mechanical twin formation was influenced by the large local stresses set up around inhomogeneities of various kinds during deformation and fracture. By calculating stresses around a moving crack, certain asymmetries (6) in twin formation on cleaved surfaces of zinc single crystals were explained.

Following with a broader programme, increasing attention was given to the dislocation description of boundaries in crystals as in twins and of boundaries between different crystal structures occurring in martensitic transformations. E. Smith (FRS 1996) was soon to join in the work as a research student, and the three of them studied general geometrical relationships in dislocated crystals in ways that could be linked usefully with continuum mechanics.

Development of the work was strongly influenced by researches in Bristol, particularly by Nye, concerning the description of deformed crystals. Bruce wanted to place on a more formal basis the mathematical representation of a crystal containing dislocations everywhere (7, 8, 13). (One of these (7) includes a preliminary account of some of the work with his research students R. Bullough and E. Smith on continuous distributions of dislocations and surface dislocations.) This was an ambitious task. It required finding a way of defining a continuously dislocated crystal. To enable a correspondence of lattice directions to be specified in such a crystal, a matrix of nine functions, together with its reciprocal, was defined at each point. Around any closed circuit of steps in the dislocated crystal the corresponding steps in a reference crystal could now be executed, the associated Burgers vector calculated and a general expression for the dislocation tensor found. With dislocations arranged so that they produce no far-reaching stress, the local crystal lattice is generated from the reference lattice at each point by matrices representing rotations. These results verified relationships between dislocation geometry and curvature tensors previously proposed by Nye, who had also considered the behaviour of a line scribed on the surface of a crystal subject to uniform bending. This scribed line is indicative of the shape change of the crystal, which results from a combination of the deformation of the lattice (in this case pure rotation) and another deformation due to plasticity through slip by dislocation movement. This resolution of the total shape strain into the shape changes produced by the lattice strain and that due to slip was discussed in several papers from the Sheffield group.

The problems of giving a dislocation description of interfaces in twins and in martensitic transformations (10), together with experimental work on the motion of simple tilt boundaries, provided further stimulus for workers at Sheffield. Suggestions were made by the group at Bristol of the possibility of deducing a formula for the dislocation content of a crystal boundary by regarding the boundary as a surface distribution of dislocation density. This led Bruce and his co-workers to introduce the concept of a surface dislocation. In slip processes, a dislocation line bounds an area over which there has been a local slip defined by the Burgers vector. The motion of a dislocation line causes slip over the region swept out. A surface dislocation is a surface separating volumes where the lattice deformation differs, in the simplest case, by a rotation. Such a surface dislocation also causes plastic deformation by its motion. It corresponds to an array of line dislocations. Ascribing tensor notation to the surface dislocation, a formal mathematical approach could then be applied to analyse a variety of experimental results. Later, it was used to discuss the discontinuities both of stress and of rotation occurring across general arrays of dislocations and, as a particular case, to confirm Frank's formula for the dislocation content of a general grain boundary. The concept of the surface dislocation was also to prove useful in discussions of the theory of the crystallography of martensitic transformations (15, 16).

Bruce considered further the geometry of the dislocated crystal and, in particular, the problem of following a prescribed crystallographic direction in it. This invoked the principal elements in a generalized space: the metric tensor, giving the length of any small vector, and the coefficients of connection, giving a law of parallelism. Calculated from the metric tensor, the connections are asymmetric, which brings in the requirement of a geometry that is non-Riemannian. In non-Riemannian space, the antisymmetric part of the connection is called the torsion tensor and the space is said to have torsion. In space with torsion, infinitesimal parallelograms do not exist. Bruce was intrigued to find that such a relatively remote mathematical structure was applicable to a practical subject that had arisen quite separately from the need to understand the deformation and strength of materials. These connections of pure mathematics with demonstrable phenomena indicated the importance of this link. The relevance was to give impetus to a revival of interest in the foundations of mechanics and the relationship with other areas. Bruce further introduced these new ideas in applying them to the theory of folding. The usefulness was established of the extensive theory of non-Riemannian spaces in its employment in, and relationship to, the theorems of dislocation theory. L. M. Brown (FRS 1982) noted a comment from J. D. Eshelby (FRS 1974) that Bruce's work cast a shaft of light on the theory of general relativity with its similar mathematical basis.

Work on generalized continuum mechanics did not prevent Bruce from pursuing his interests in problems more immediately relevant to metallurgical practice. With others he wrote several papers on martensitic transformations (9), on more practical aspects of dislocation theory (11, 12, 14) and on the role of hydrogen in the cracking of steel (17, 25). With A. G. Crocker, Bruce ventured into an early use of the Ferranti Pegasus computer, which had been purchased by the United Steel Companies for their Cybernetics Department and on which the university was to be allowed limited time each week. Indeed, he made, with Crocker, a visit to the machine at Ferranti in London to test programs before the machine was delivered.

After Bruce's appointment to his personal chair in 1962, he gave his Inaugural Lecture with the title 'Mathematics and materials'. It was not published, but its main theme was that, on the one hand, pure scientists would find interesting problems of pattern in technology and, on the other, that technologists should welcome the support and interest of the pure scientist. He noted that, according to the dictionary, a material was a thing from which something was made. This perhaps epitomized the difference in viewpoint of the pure and applied sciences. However, striking analogies of pattern between mathematical ideas and the real world had almost philosophical implications, and there were plenty of interesting problems to be found in practice. A quotation from Bruce's summing up found its way into a local newspaper: 'Do not look only from your high towers at a distant prospect of Attercliffe [an industrial area in the Don valley within Sheffield], but go down sometimes and see what actually happens there.'

In the following year Bruce was the recipient of the Rosenhain Medal of the Institute of Metals.

Research on fracture

Looking for further practical applications of the new dislocation concepts and continuing to benefit from discussions with Cottrell, Bruce's small but powerful research group directed much of their attention to problems of fracture, its characteristics and its avoidance. These problems were crucial in the design of nuclear reactors for power generation.

Importantly, Cottrell had proposed a simple model to allow for the plasticity at a crack tip. A crack that spreads throughout a large structure before the regions remote from it show that any sign of plastic deformation presents an engineering catastrophe. To prevent such occurrences, particularly recalling problems that had arisen from the spectacular failures in welded 'Liberty' ships during the war, considerable attention was already being devoted in numerous places to the understanding of fracture mechanics. The importance of plasticity in the material was widely recognized, but problems remained in evaluating the respective roles of elasticity and plasticity (18, 19). Cottrell, in his lecture on 'Why some brittle solids are strong', stated:

> to develop this idea [the propagation of a brittle fracture] an elastic–plastic theory was needed. I soon wrote down the mathematical equations representing this situation and equally quickly realized that I could not solve them. And so I approached my old friend and research collaborator, B. A. Bilby, a much better mathematician, at the University of Sheffield.

Bruce was able to deal with this and, with input from his research student K. H. Swinden, arrived at analytical solutions that had practical implications. A series of material parameters characterizing crack advance were identified. These could be estimated or measured in a structure and an appropriate system of inspection and testing could be set up to reduce catastrophic occurrences to a minimum.

Procedures involved an assessment of the size of plastic zones and the effect of the mode of loading in relation to specimen size and geometry. Among the parameters characterizing the advance of a crack, an important feature is the opening displacement that occurs at the crack tip if it blunts through the onset of plastic deformation in that region. Another parameter introduced to discuss tougher materials exhibiting such plasticity and some crack growth is the J parameter, which can be calculated from the elastic–plastic field along a path remote from the crack. In fracture mechanics it is usual to think of three idealized modes of remote loading of a crack, the actual loading usually being a combination of these. Bruce and Swinden considered the simplest case, in which the crack plane is under shear in a direction parallel to the crack line. They showed that the relative displacement due both to the crack and to the plasticity beyond its tip can then be represented (20) by continuous distributions of dislocations in the crack plane. The distributions are determined so that under remote loading there is no stress over the region representing the crack but a finite stress (representing a plastic yield stress) in the plane beyond the crack tip. As a result there is a relative displacement at the crack tip due to the dislocations that have spread against finite resistance into the region representing plasticity. Thus the model provides an estimate of the crack opening displacement.

At this stage, an earlier paper by D. S. Dugdale was noted on 'Yielding in steel sheets containing slits', in which the slits were perpendicular to the stress. Here the approach was from a somewhat different mathematical viewpoint, not using dislocation theory. The two different approaches, however, were complementary and led to the Dugdale, Bilby, Cottrell, Swinden (DBCS) or 'strip yield' model, which has had widespread application in the interpretation of fracture and fatigue. Its power lies in its provision of simple analytical relations between important parameters governing crack behaviour, particularly between the remote load, the elastic modulus, the relative displacement that occurs at the crack tip and the stress resisting dislocation motion beyond it. This work was also valuable in assessing the importance of notches in fatigue (22, 24). Cottrell made immediate use of the key results in the derivation of a criterion of notch sensitivity. From it he was able to discuss a wide range of fractures, from the purely brittle to the fully ductile fast failures that could occur in pipelines and plate structures. The general model and its implications were reviewed by Bruce and Eshelby (23). The value of this work has been increasingly appreciated, as exemplified in its underpinning of procedures developed by workers in the Central Electricity Generating Board in their preparation of Code R6 for risk assessment of failure.

Other academic involvements at Sheffield

Within the university, Bruce was active in teaching as well as research and gave lectures to both undergraduate and postgraduate students. A general view of these students was that the lectures were not always easy to comprehend immediately but, in looking back at their content at a later time, the students came to realize their rigour and value in enhancing understanding of many of the new, exciting and significant developments that were then transforming and greatly accelerating progress in metallurgy. Additionally, Bruce had a major role in establishing a postgraduate course in conjunction with the Department of Applied Mathematics on 'Theory of deformation, flow and fracture'.

The early 1960s were a difficult time for Bruce, going through divorce in 1964, with the three children continuing their education in Sheffield and visiting their mother in Nottingham at weekends and during school holidays. Happily, in 1966, he was again married, this time to Lorette Thomas, an independent research worker in the Department of Community Medicine at Sheffield, and they had two children. At his work in the university there were upheavals through disagreements over Faculty policy and the allocation of new posts. This led to changes in Faculty structure in 1966 and the creation of a small new department, named the Department of the Theory of Materials, with Bruce at its head with his title changed to Professor of the Theory of Materials. It was housed in space made available in the Elmfield Building of the Department of Glass Technology that had joined the Faculty of Metallurgy in 1962. There were some benefits in this departmental independence, but the location was some distance from other departments of pure and applied science with consequent drawbacks in making more difficult the informal association with others that could have been of mutual benefit. There was little in common between the Theory of Materials staff, with their focus of attention on faulted crystals, and the interests of their only neighbours, the glass technologists; however, some mutual concerns were found. Bruce was able to demonstrate that Eshelby's earlier study of stresses around ellipsoidal inclusions in stressed solids could be extended to determine the conditions under which bubbles within, and in relative motion with, viscous liquids would remain ellipsoidal. This became of interest to geologists as well as those concerned with glass manufacture.

From its foundation in 1966, the new department soon began to flourish and establish its own reputation. Eshelby was looking for a new appointment at that time (as Bruce was aware) and joined the staff as Reader. Five years later he was promoted to a personal chair. Dr C. Atkinson (FRS 1998) (later to become Professor of Applied Mathematics at Imperial College, London) was appointed Lecturer. There was a secretary and a junior programmer to link with the support available from the University's Computer Services. Soon afterwards, the department was strengthened by the appointments of I. C. Howard as Lecturer (later becoming Professor) and G. E. Cardew, with extensive previous experience, as Senior Programmer. The department addressed a wide range of important problems. These were often difficult conceptually and mathematically but the staff worked effectively, both individually and collectively, and were always were quick to get to the fundamentals. An output of highly significant research was maintained and a steady flow of research students continued. Atkinson, as well as collaborating with Eshelby in solving important problems in the dynamics of fracture, was able to provide the first analysis of the interaction of a dislocation with a crack in an anisotropic medium.

Acknowledging the increasing complexity of his subject area and believing that understanding was necessary if theoretical results were to be used intelligently, Bruce wrote elementary accounts of dislocation theory (21) to aid in its comprehension. He also wrote a valuable review on developments in the theory of fracture (26). Concurrently, he made further advances, notably in the systematic study of shuffling movements in deformation twinning and in the use of the slip field model in notch fatigue.

The department suffered a severe blow with the sudden death of Eshelby in 1981. As a tribute to him, the International Union of Theoretical and Applied Mechanics held the Eshelby Memorial Symposium in Sheffield in April 1984, and Bruce played a large part in its planning. The event was a great success, with a high proportion of world leaders in the field of deformation and fracture in attendance. The proceedings, entitled *Fundamentals of deformation and fracture*, were edited by Bruce in collaboration with K. J. Miller, then Head of the Department of Mechanical Engineering at Sheffield, and J. R. Willis (FRS 1992) of the University of Bath; the volume was published by Cambridge University Press. Bruce presented an excellent introductory lecture and review (28) at the Symposium focused on the contributions that Eshelby had made.

Bruce gave several memorable and much-valued lectures at major institutions and at conferences throughout his career, although he rarely sought such opportunities. When invitations came along he sometimes preferred that his collaborators present papers rather than himself. This was not due to shyness but to a genuine wish that his colleagues and students should get both the experience in paper presentation and an appropriate share of the credit for the work done. For Bruce, much of his interaction with others came from innumerable requests from people elsewhere to visit Sheffield to have discussions with him. Most of the visitors found such interactions highly rewarding and were delighted to have contact in this way. Many were surprised by, but admiring of, his selfless attitude where problems and not personalities were always the focus of attention.

The long tradition of metallurgical work at Sheffield had given metallurgy the status of a Faculty within the university, initially comprising only the one department, the Department of Metallurgy. The number of departments that this Faculty contained gradually extended with incorporation by transfer in 1962 of the already well-established Department of Glass Technology and with new departments, the Department of Ceramics and the Department of Theory of Materials, joining on their formation. The Faculty name was later changed to become, more appropriately, the Faculty of Materials, and the departments within it concerned with non-metallic materials were combined and extended to form the Department of Ceramics, Glasses and Polymers. The post of Dean was rotated between the senior members of staff, and Bruce served as Dean on two occasions, each for the allocated period of three years. Although not seeking roles that were largely administrative, Bruce was nevertheless effective as Dean and it gave him more opportunity for contact with staff throughout the university. He served diligently on several committees that this post required. In these, he was widely respected by staff in all disciplines for his thorough academic approach and fairness. He suggested improvements that he felt might be effective in minor changes in several areas but understood that it was never easy to predict the outcome of the Senate's debate. Although appreciating the need for specialization to achieve academic depth, Bruce nevertheless felt that university staff should not feel too restricted in their range of study. One small disappointment was the Senate's declining his proposal to alter the name of the Department of Biblical Studies to the Department of Religious Studies.

Approaching and after formal retirement, Bruce continued to look at problems within the university's Department of Mechanical Engineering, aiding their research in studies on fatigue. The extension of earlier work (29) gave opportunity for improved predictions of the conditions leading to fracture and fatigue. For such evaluation, extensive numerical work was essential. Fortunately computer support continued to be available from G. E. Cardew, and the contribution paved ways to further progress (27). Bruce also continued to benefit from his long and fruitful collaboration with I. C. Howard, who had moved from Bruce's former department to the Department of Mechanical Engineering. Along with use of finite element computer programs developed at other institutions, a program, TOMECH, was formulated at Sheffield and first used to examine the effect of specimen geometry on the stress and strain at the tips of stationary cracks. It was also used in alternative approaches to fracture problems, notably those based on the concepts of 'damage theory'. In this, the gradual failure of the material ahead of the crack is explicitly modelled so that in this region the load-bearing capacity gradually decreases with consequent crack advance. The approach assisted in the extrapolation of results on relatively small specimens to predict the behaviour of much larger engineering components. It also proved valuable in its predictions of the conditions of failure in the walls of cylinders rapidly rotated about their axes (30), thus linking with experimental data relevant to the design and performance of pressure vessels.

The growth in computer power progressively allowed more extensive use of finite element programs and an increasing number of workers to enter the field of fracture assessment. More procedures were devised and some were incorporated into codes of practice. Bruce made a detailed study resulting in a better understanding of the relation between the *R*-curve procedure originating in the USA and the R6 and PD6493 procedures devised in the UK. This was a complex area but provided the opportunity to introduce further variables. Bruce's final series of papers, on failure assessment diagrams, showed how such variables (31) could be incorporated. The value of this work was recognized by his being awarded the Griffith Medal by the European Structural Integrity Society in 1994.

Figure 2. Bruce playing a game of croquet in his garden. (Online version in colour.)

A colleague once asked some of his former research students (two of whom became FRS), who had worked with him on the continuum of dislocations, why they had not continued working on it afterwards. They replied that it was too hard! This never stopped Bruce from continuing to study erudite subjects long after his early retirement in 1984.

Activities outside the university

In parallel with his working life, Bruce greatly enjoyed activities with his family. They had interests indoors in music and literature as well as pursuits in outdoor life. In music, Bruce took piano lessons late in life. He never claimed a high level of competence and declined public performances, though he prepared for examinations extending to Grade 6. His receipt of professional music tuition and his dedication to serious study were further indications of his perpetual desire to aim at accuracy and precision in all he undertook.

Over a long period, croquet remained an enjoyable activity, regulated by Bruce's knowledge of the rules, which was so thorough that decisions were rarely challenged by his opponents. His large garden was excellently adapted for pursuit of the game, and many visitors recall their enjoyment there and the challenges presented. Bruce continued to play (figure 2) until shortly before his death. His wife felt that his physically active lifestyle, starting in his early years and involving swimming and cycling over long distances, had contributed to a long and healthy life.

Figure 3. Bruce on his yacht *Lady Be' Ann* in the North Sea. (Online version in colour.)

Bruce's prime interest was in the sea and ships, inspired by his schooldays and the environment in Dover. In 1969 this was revived to become a practical and time-consuming involvement when the family purchased a small seagoing wooden yacht, *Ocean Baby*, moored on the river Humber at Grimsby. Such a location, with complex tidal conditions, required considerable seamanship but Bruce enjoyed the challenges it created. After a trip on the Dutch canals in 1976, during which *Ocean Baby* got a rope around her propeller just as she was about to pass under the huge Maastricht Bridge raised for her at rush hour, the decision was taken to replace her by a 29-foot fibreglass Bermudian sloop *Lady Be' Ann* (figure 3). In 1978 she was taken from Grimsby into the French canals at Saint-Valery-sur-Somme. Finally, in 1986 a long voyage was planned over three summers during which the boat was taken via the French canals and on to the Greek island of Lefkas.

In retirement Bruce and Lorette were great companions for one another, and family gatherings gave much pleasure to them both. They encouraged their children, grandchildren and great-grandchildren in a wide range of activities, and took much pride in their development and progress.

Bruce's only daughter, Elisabeth, died in 2009, and his eldest son, John, died in 2011. Bruce is survived by his wife, Lorette, and three sons, Tom, Richard and Nicholas, together with their wives and Elisabeth's husband, Marcel, and John's wife, Lesley. They and the twelve grandchildren and three great-grandchildren will miss Bruce greatly but remember him with much love, respect and affection.

Concluding notes

At the university, Bruce's work was always characterized by deep thought, clarity and precision. This made him appear sometimes remote, but not to his closer colleagues and many friends, who valued his thoroughness, extensive knowledge and wide interests. The members of staff who worked with him and all his research students held Bruce in high esteem. It is notable that their beginning in his research group almost invariably led to their achievement of high-ranking appointments: some of them remained in academic research, some moved to high-technology companies and consultancy, and others attained managerial leadership. Although Bruce was regarded mainly as a theoretician, much of his work and that of his group provided results that had practical applications. The work demonstrated the continuing importance of continuum mechanics while emphasizing the value of understanding defects in materials on an atomic scale. Linking the microscopic scale with the macroscopic was a major feature.

There is now widespread recognition of the immense value of dislocation theory in understanding the properties of crystalline materials. Bruce's work contributed greatly to the provision of a firm mathematical basis for this situation. Throughout, Bruce's work demonstrated that a concentration on what may first seem to be of purely academic interest can have profound technological benefits.

Honours and awards

1963 Rosenhain Medal, Institute of Metals, London
1977 Fellowship of the Royal Society
1994 Griffith Medal, European Structural Integrity Society

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The frontispiece photograph was taken in 1992 by Bruce's daughter.

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