NATIONAL ACADEMY OF SCIENCES

BRUCE CHALMERS

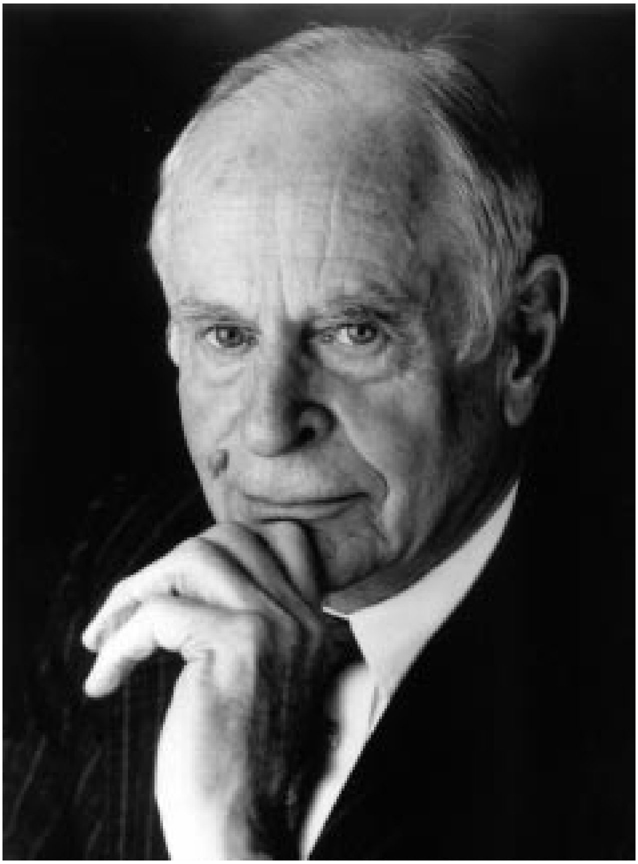
1907—1990

A Biographical Memoir by

DAVID TURNBULL

Biographical Memoir

National Academies Press
washington d.c.



Bruce Chalmers

BRUCE CHALMERS

October 15, 1907–May 25, 1990

BY DAVID TURNBULL

BRUCE CHALMERS HAD A notable career as a scientist, educator, and editor. He outlined his career in his professional biography, which was published in the thirtieth anniversary volume[1] of "Progress in Materials Science," a series for which he was the founder-editor. This volume, consisting of articles by some of his former students and professional colleagues, was published to honor him. I have relied heavily on that account[2] in preparing this memoir.

Bruce was born in 1907, a son of Stephen and Clara (Rosenhain) Chalmers, and was reared in London. His father, a descendent of the Scottish Camerons, was a mathematics teacher; he died in 1919, when Bruce was twelve years old. Bruce's inclination toward science developed quite early and was stimulated in part by his father and especially his older brother Alan, who became a physicist and professor at the University of Durham. However, the major influence on his choice of career was that of his maternal uncle, Walter Rosenhain, a leading metallurgist who, during World War I, was superintendent of the Department of Metallurgy and Metallurgical Chemistry in the National Physical Laboratory. Rosenhain became well known for developing one of the earliest models for intercrystalline boundary structure. It is interesting that Bruce came, by a somewhat circuitous route, to play a leading role in developing the much more sophisticated modern theory for such structures.

In a review published in 1917,[3] Rosenhain wrote with great clarity and eloquence of the emergence of a "New Metallurgy" based on fundamental research in chemistry and physics. Bruce's career contributed greatly to the development of strong bonds between metallurgy and physics and chemistry, and the continued advancement of the "New Metallurgy", but with somewhat more emphasis on the metallurgy bond to physics than to chemistry.

Bruce lived at home throughout his secondary and university training. He attended University College of London University and earned a B.Sc. in physics in two years, bypassing the normally required third year. He was accepted as a Ph.D. student by Professor of Physics E. N. DaC. Andrade. Bruce was highly inspired by Andrade, both for his achievements as a scientist and as an educator. Andrade in 1910 "was one of the first to recognize that the mechanical behavior of metals could properly be regarded as a problem in physics." He discovered the $t^{1/3}$ law of creep. For his Ph.D. thesis, Andrade suggested that Bruce investigate the change in resistivity accompanying the creep of metals with a hexagonal crystal structure, such as cadmium. Indeed, the resistivity did change with deformation, reflecting the change in crystallographic orientation with slip. In connection with his investigation, Bruce had to put together X-ray diffraction equipment, which was then lacking in the physics department. Bruce learned much from Andrade about how a professor and research student should interact most effectively. Bruce greatly admired Andrade's way with research students, which was to have them *work* with him rather than *for* him and to allocate credit fairly for any discoveries.

Bruce received his Ph.D. degree in 1932 during the depth of the Great Depression, when positions were difficult to find. After a year of postdoctoral study he was appointed lecturer in physics at Sir John Cass College of London University, a technical institute that mainly served part-time evening students who had taken industrial jobs immediately following their secondary education. Bruce taught in the evenings five times weekly, so his days were more or less free for research.

At this time, many physicists shared Andrade's interest in the plastic properties of single crystals, and G. I. Taylor, Egon Orowan, and others were developing the dislocation models for plastic flow. Bruce was drawn into these activities, and he devised high precision measurements of plastic creep rates of single crystals at low stress levels. He developed a simple method of growing tin single crystals with any specified crystallographic orientation. Understanding the flow behavior of single crystals would be essential to interpreting that of the more complicated polycrystalline solids. In the course of his investigations, Bruce found that one of his presumed single crystals actually was composed of two crystals separated by a boundary along the entire length of the cylindrical specimen. From visual and optical microscope observations, he noted that all the crystals he grew exhibited sub-boundaries and other imperfections. The origin, structure, and property effects of these imperfections fascinated Bruce, and they became the focus of his research throughout his career.

After five years at Cass, Bruce accepted a position as physicist at the Tin Research Institute, a laboratory sponsored by the International Tin Research and Development Council. In addition to his studies of the mechanical behavior of tin, he investigated the physics of the process of making tin plate by dipping steel into molten tin. He was required to develop methods for examining the micro-topography of the surface of the tin layer and to do theoretical work on the origin of the porosity often present in the layer.

In 1938 Bruce married Ema Arnouts, who was a warm and supportive companion throughout his life. They became the parents of one son, Stephen, and four daughters, Carol, Jane, Alison, and Heather.

Soon after the beginning of World War II, Bruce joined the metals research section of the British Ministry of Supply, and he investigated the heat treatment of armor piercing shot and the non-destructive evaluation of their quality. Early in 1944 he was appointed head of the Metallurgy Division of the Royal Aircraft Establishment at Farnborough, where he was concerned with problems of materials failures, as in aircraft crashes, and development of alloys with high strength and low density. These problems led him more deeply into the general area of structure-property relations, which are central to physical metallurgy.

In 1946 he joined the Atomic Energy Research Establishment opening at Harwell as head of its Metallurgy Division. There he formulated a program directed at the development of nuclear reactor materials and assembled a research staff to carry it out. His staff members remember him as an inspiring leader, but he found the burdens and bureaucratic controversies attending administration quite distasteful. Having enjoyed his teaching experience at Cass, he was attracted to the possibility of returning to academia.

This prospect soon materialized, and in 1948 he became a professor of physical metallurgy at the University of Toronto. At Toronto he attracted a large group of students in whom he aroused a great enthusiasm for metallurgical research. It was his practice to have most of his research group accompany him to National Metallurgical Society meetings in the United States, where Bruce introduced them to leading scientists. The students eagerly attended the technical sessions and at intersessions boldly assailed the speakers with ideas and often-embarrassing questions about their results.

This practice of promoting student participation in scientific meetings reflects his sagacity as an educator and the close, cordial relations he always had with his students at Toronto and later at Harvard. He and his students performed the experiments and analyses that laid the foundations of our present understanding of the origin and nature of the grain and subgrain morphology formed in the crystallization of liquids. Their analyses took due account of the heat and material transport and interface movement and morphology attending crystallization. Especially important was their concept of “constitutional undercooling”, which accounted for the role of impurities in the development of cellular and dendritic structures. He and student Karl Aust at Toronto grew sets of tin and lead bicrystals with a range of misorientations and measured the relative grain boundary energy dependences on the crystallographic misorientations. These energies and those of FeSi alloys measured independently by C. B. Dunn at General Electric were in remarkable agreement with the predictions of the dislocation model for tilt-type grain boundaries developed at Bell Labs by W. T. Read and William Shockley.

In 1953 Bruce accepted appointment as Gordon McKay professor of metallurgy in the Division of Applied Sciences at Harvard University. This position attracted him in part because the absence of departmental boundaries would permit him to interact freely with the solid state physics and applied mechanics groups in the division. Then, and for a considerable time thereafter, graduate students were admitted to the division and to the physics department with no initial commitment to any professor. Thus, they had one to two years to explore possible Ph.D. thesis topics and to seek an advisor. This policy meant that each professor had access to a brilliant group of students, and Bruce and his successors in the materials science-metallurgy option benefited greatly from it.

During the period 1930-70 in the United States and Europe there was extensive interdisciplinary cooperation of metallurgists with physicists, physical chemists, and applied mechanicians, which transformed metallurgy from an art to a science and laid the foundation for what we now label materials science. Among the physicists and physical chemists who were most prominent in effecting this transformation were Frederick Seitz, Clarence Zener, Conyers Herring, Charles Frank, Nevill Mott, W. Shockley, John Bardeen, and Harvey Brooks. From the metallurgical side there were Cyril Stanley Smith, L. S. Darken, Alan Cottrell, Morris Cohen, Paul Beck, R. F. Mehl, C. S. Barrett, A. Guinier, J. H. Hollomon, and other members of his group at the General Electric Research Laboratory.

Through his activities as a scientist and editor, Bruce played a central role in this transformation. He was the founding editor of the continuing series of treatises "Progress in Metal Physics," now "Progress in Materials Science." Bruce and co-editors Ronald King. W. Hume-Rothery, J. W. Christian, and T. B. Massalski, who joined him from time to time, attracted a very distinguished group of contributors from diverse fields. These volumes were highly influential all over the world in the education of graduate students studying metallurgy, solid mechanics, and materials science generally. They also played an important part in defining the scope and limits of materials science. Later Bruce became the first and longtime editor of a newly founded (in 1953) journal *Acta Metallurgica* (now *Acta Materialia*). This journal was founded in response to the impression that the metallurgical society journals had become too limited in their scope and too permissive on the quality of the papers they accepted. Bruce imposed high standards for publication, as he did for articles solicited for the Progress series. *Acta Metallurgica* became the journal of choice for metallurgists and other materials scientists worldwide, and with the Progress volumes it set the standard for research in these areas. While imposing high standards on the papers accepted, Bruce was highly receptive to new ideas and theories and exercised a liberal policy on their acceptability for publication. Capt. Robert Maxwell's Pergamon Press published *Acta Metallurgica* and ultimately the Progress volumes. Bruce had a sometimes-adversarial relation with Maxwell, who from Bruce's standpoint was often too concerned with the commercial aspects of publishing scientific articles.

At Harvard, Bruce continued to guide research on solidification and the structure and behavior of grain boundaries. He and his students demonstrated that the appearance of equiaxed grain structures in the crystallization of pure liquids generally results from dendritic breakup. Often this breakup is effected by convective currents in the liquid. They showed that, when these currents are suppressed in molten aluminum by imposition of a magnetic field, a columnar morphology forms in crystallization under conditions where an equiaxed one normally would have appeared. Also, they developed a beautiful visual demonstration of dendritic breakup in the freezing of water in an "ice machine" programmed to cycle water between a temperature above its freezing point and a lower temperature at the point of dendritic breakup. This experiment was on exhibit at the Brussels World's Fair in 1958, and is now sometimes displayed at the Boston Museum of Science.

At Harvard, he also wrote several books, one of which was the widely cited *Principles of Solidification* (1964); two other books were *Physical Metallurgy* and *Energy*. Most of his students and postdoctorals were stimulated, partly by his example, to dedicate their entire careers to science, and many have achieved distinction in academia, government, and industrial high-technology laboratories. He and I were colleagues at Harvard from 1962 on. When we discussed theoretical ideas or models, he always focused on the experimental support for them. In his quiet low-key way, he exerted tremendous influence on the development of interdisciplinary relations and the consciousness of a materials science bonding the underlying disciplines.

In the latter part of his Harvard career, Bruce developed a strong interest in undergraduate education, and in 1964 President Pusey appointed him master of Winthrop House. Pusey noted Bruce's remarkably broad intellectual perspective and his deep appreciation of the humanities. From my association with Bruce, I can attest to his wide knowledge of literature and to his deep insights into history and politics. The Harvard houses were patterned after the college system of Cambridge and Oxford. While each provided a community for about 400 students, they never acquired the central educational and policy roles in the university that the British colleges have. Nevertheless, Bruce with Ema's enthusiastic support fostered a friendly, intellectually vibrant atmosphere in Winthrop House. Often outstanding persons in a variety of fields visited the house to speak and interact with the students. Bruce had a strong rapport with the students, and the *Crimson*, the college newspaper, while normally critical of the university administration, often lauded Bruce and rated him one of the best of the house masters.

During the period 1967-72 student activists often disrupted Harvard and other universities. At Harvard, the activists sought to have the university administration and faculty publicly denounce the United States' Vietnam policy and to bar the Reserve Officer Training Corps from the campus. In the spring of 1968 a militant group occupied the central administration building after ousting the college administrators. President Pusey called in the outside police who removed, not too gently, the occupying students. This action was met with great indignation by students and faculty with more moderate views, as well as by the militants, and a college-wide student strike was threatened. The student body as a whole met in Harvard Stadium to consider a strike. One of the few faculty members invited to speak at this meeting, Bruce gave a conciliatory talk, and the strike was voted down. However, the college was disrupted for the rest of the spring term by fierce debates and various actions threatened by the most militant students. The extreme militancy and unrest persisted until the spring of 1972, when it ceased rather suddenly.

Throughout this period, Bruce continued to play a mediating role in reconciling the students and the administration, and thwarting the rashest actions (e.g., torching a university building) attempted by student radicals. His was always a moderate voice counseling the administration against harsh action toward the student protesters and trying to convince the students that their real quarrel was with the national—rather than the university—administration.

Also in his later years at Harvard, Bruce became especially interested in the problems of energy production and conservation. Based on his knowledge of solidification mechanisms, he conceived a process for casting silicon in a single crystal ribbon form, which might be suitable for photovoltaic applications and which could be processed with minimal material loss. He and his postdoctoral fellow Tom Surek induced the Mobil Tyco Corporation to sponsor research to test and exploit this idea, and Mobil Tyco Solar Energy Corporation carried on such a program for several years. A number of serious difficulties were overcome, but eventually a process labeled edge-defined, film-fed growth (EFG) was developed. Throughout this development Bruce played a central role in giving advice and mentoring the engineers and scientists working on the project.

A German corporation, ASE Americas, undertook the actual commercialization. Its products are hollow Si tubes with octagonal cross sections. Wafers are formed from the octagonal crystal by laser cutting. Overall materials losses are less than 8%, compared with 50% in the processing of bulk crystals. The company produces modules in the form of octagons about 10 cm across each face and approximately 300 microns thick. Most of the modules produce 50 watts of electricity. Currently the annual production is 4 megawatts of solar cell capacity, but production is being expanded quite rapidly so that shortly production will reach some 10 megawatts per year. By the year 2000, about 20 megawatts of capacity is projected. The current cost of the finished product is about $4.00 per watt. The company's solar cells operate at an efficiency of 14%.

Bruce and Ema left Winthrop House in 1973 and moved to Falmouth on Cape Cod. He continued his teaching at Harvard until 1977, when he retired as professor emeritus. He kept up the consulting already alluded to and played an active part in Falmouth community affairs. In 1986, as vice-chairman of the Falmouth Tricentennial Committee, he wrote an intriguing history of the town (published in the *Book of Falmouth*), covering the entire period from the founding of the town to 1986. His recreational activities included sailing, hiking, reading, writing, photography and color printing, and fabrication of various objects in his home workshop.

In addition to election to the National Academy of Sciences (in 1975), he received a number of other noteworthy honors, including a fellowship in the American Academy of Arts and Sciences, honorary memberships in various foreign scientific and technical societies, the Saveur Award from the American Society of Metals, and the Clamer Medal of the Franklin Institute. In 1989 the Minerals, Metals, and Materials Society created the Bruce Chalmers Award, and Bruce was the first recipient—for distinguished contributions to the science and technology of solidification processing.

In 1988 he learned that he had a condition that turned into multiple myeloma. He courageously continued his consulting and community activities until his death on May 25, 1990. Ema, their five children, and eleven grandchildren survive him.

I AM INDEBTED TO Ema and Stephen Chalmers and Alison Chalmers Rodin for supplying much personal information on Bruce's life. I thank Professor John Hutchinson of Harvard University and Kalies Juris, now vice-president for research at ASE Americas, for supplying information on the status of the silicon ribbon strip casting process.

NOTES

1. B. Chalmers, professional biography. In *Progress in Materials Science,* Chalmers anniversary volume, ed. J. W. Christian, P. Haasen, and T. B. Massalski. Pergamon: New York, 1981.

2. Bruce Chalmers memorial minute. Harvey Brooks, William Paul, Frans Spaepen, and David Turnbull (chair), Faculty of Arts and Sciences, Harvard University, May 21, 1991.

3. W. Rosenhain. The modern science of metals, pure and applied. In *Science and the Nation,* ed. A. C. Seward. Cambridge University Press, 1917.

SELECTED BIBLIOGRAPHY

1936

Micro-plasticity in crystals of tin. *Proc. R. Soc. Lond. A* 156:427.

1940

The mechanical effects of intercrystalline boundaries. *Proc. Phys. Soc.* 52:127.

1948

With R. King and R. Shuttleworth. The thermal etching of silver. *Proc. R. Soc. Lond. A* 193:465.

1950

With K. T. Aust. The specific energy of crystal boundaries in tin. *Proc. R. Soc. Lond. A* 201:210.

1953

With W. A. Tiller, K. A. Jackson, and J. W. Rutter. The redistribution of solute atoms during the solidification of metals. *Acta Met.* 1:428.

1954

Melting and freezing. Inst. of Metals lecture. *Trans. AIME. J. Met.* 6:519.

1955

With C. Elbaum. The topography of solid-liquid interfaces of metal crystals growing from the melt. *Can. J. Phys.* 33:196.

1958

With K. A. Jackson. Freezing of liquids in porous media with special reference to frost heave in soils. *J. Appl. Phys.* 29:1178.

Growth of crystals of pure materials and of the solvents of solutions. In *Growth and Perfection of Crystals*, ed. R. Doremus, B. W. Roberts, and D. Turnbull, p. 291. New York: Wiley & Sons.

1962

With P. Doherty. The origin of lineage substructure in aluminum. *Trans. Met. Soc. AIME* 224:1124.

1963

Structure of ingots. *J. Aust. Inst. Met.* 8:255.

1964

Principles of Solidification. New York: Wiley & Sons.

Interactions between particles and a solid-liquid interface. *J. Appl. Phys.* 35:2987.

1965

With R. B. Williamson. Crystal multiplication without nucleation. *Science* 148:1717.

Dynamic nucleation. In *Structure, Properties, Solid Interaction,* ed. T. J. Hughel, p. 308. Amsterdam: Elsevier.

1966

With D. R. Uhlmann and T. P. Seward III. The effect of magnetic fields on the structure of metal alloy castings. *Trans. Met. Soc.* 235:527.

1969

With M. Weins, H. Gleiter, and M. F. Ashby. Structure of high angle grain boundaries. *Scripta Met.* 3:601.

1971

Structure of grain boundaries. In *Structure and Properties of Metal Surfaces.* In honor of Professor Honda, Japan Honda Memrial Commemoration.

1972

With H. Gleiter. High angle grain boundaries. In *Progress in Materials Science.* New York: Pergamon.