BIOGRAPHICAL MEMOIRS

Robert Weierter Balluffi

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Elected to the NAS, 1982

A Biographical Memoir by Adrian P. Sutton

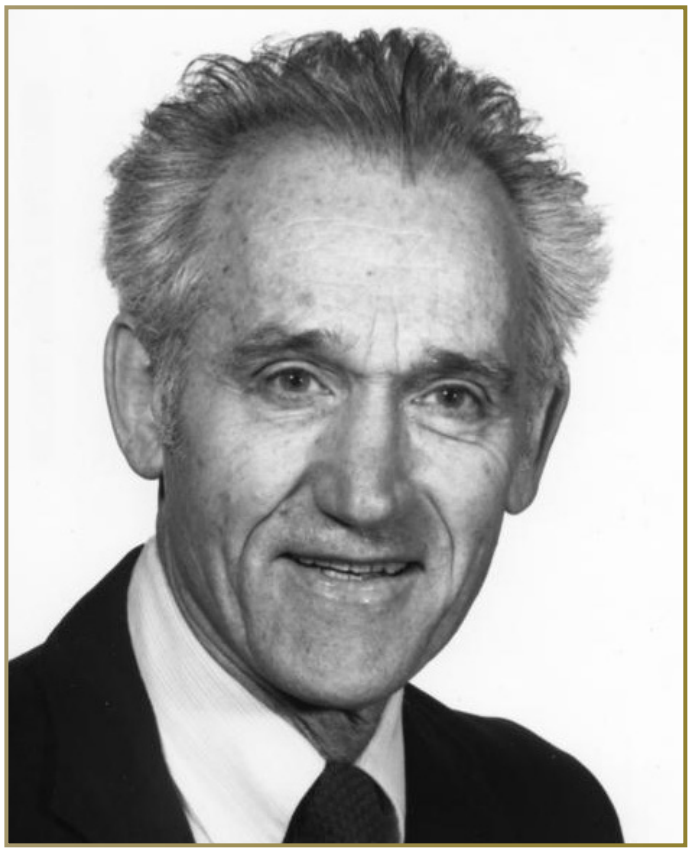

Figure 1 Robert W. Balluffi. *AIP Emilio Segrè Visual Archives*, Physics Today *Collection*.

Robert W. Balluffi, known as Bob, made outstanding contributions to the science of crystalline materials. Many properties of crystalline materials, including strength, ductility, resistance to fracture and resistance to radiation, are determined by defects in the crystal structure. His measurements of the structures and properties of defects in crystalline materials, especially metals, are among the most definitive in the history of materials science. His focus was the design and execution of experiments to make accurate measurements of defect properties and to unravel complex defect processes such as radiation damage, sintering, and diffusion in materials. His career began at a time when prominent solid-state physicists were also interested in defects, and he worked with them to turn the art of metallurgy into a science, which became the forerunner of modern materials science.

There were many ground-breaking Balluffi experiments, but two stand out as milestones in the development of materials science. The first was the measurement of the free energy of formation of vacancies (missing atoms) in aluminum, copper, silver, gold, and dilute aluminum-silver and aluminum-magnesium alloys which he performed with Ralph Simmons. The second was the observation and characterization of dislocations in grain boundaries in manufactured bicrystals with pre-determined planes and misorientations, which was carried out with Tilman Schober. The elegance and originality of these experiments is striking. They provided quantitative data to test theories of point defects and grain boundaries. As the subject of physical metallurgy developed and evolved into materials science, Bob became increasingly involved in its teaching and curriculum development, and he authored or co-authored three graduate textbooks. He was as passionate about teaching as he was about research.

Early Life and Education

Bob was born in Bayshore, Long Island, New York, and as a child lived in a settlement house on the Upper East Side of Manhattan with his parents and younger sister Carol. Neither of his parents had any advanced education or connection with science or engineering. His father, Frank Balluffi, was a self-educated man and a "Sunday painter," whose paintings

won prizes throughout his life. Frank Balluffi's efforts to pursue a career in art were frustrated, however, and he became a social worker. Nevertheless, he inspired in Bob a lifelong love for painting. His mother, Louise Balluffi (née Weierter), was the rock of the family and took part-time jobs in the settlement house to supplement the family income.

Bob graduated from Hunter College Model Grade School in Manhattan and qualified for admittance to Stuyvesant High School, which specializes in math, science, and technology, in 1938. Soon after completing his freshman year, his father was laid off, and the family moved up the Hudson River to Peekskill. Peekskill High School was a breeze after the rigorous Stuyvesant, and Bob diverted much of his energy into baseball, swimming, and playing jazz trumpet. As he approached the end of his high school years, he had no strong convictions about what career he should pursue. His parents persuaded him to pursue a science or engineering career and apply for admittance to the Massachusetts Institute of Technology (MIT). His high school grades had slipped at Peekskill High School, but after working hard in his senior year he gained admittance to MIT in 1941.

In his freshman year, Bob had to work hard to catch up with his peers. He began coursework in physical metallurgy in his sophomore year and decided to major in it. After two years at MIT, his studies were interrupted by World War II. He was drafted into the Army Specialized Training Program (ASTP), where he received infantry basic training during the summer of 1943 in sweltering heat in Texas. His ASTP training continued at MIT, where he was required to study mechanical engineering. After two semesters, his ASTP training was terminated, and he was assigned as a foot soldier in the 309th Regiment, 78th Infantry Division. He saw combat in the Battle of Hürtgen Forest and the Battle of the Bulge. He was awarded a Bronze Star for heroic action in the latter. He also took part in the crossing of the Rhine at Remagen and elimination of the Ruhr pocket of German forces. In 1946, Bob resumed his studies on physical metallurgy at MIT and received his bachelor of science degree in June 1947, having lost only two academic years to the war.

Morris Cohen at MIT offered Bob a research position leading to a doctor of science degree in 1950, on the behavior of carbides during the tempering of chromium steels. Although Bob had never considered a life in research, he found it exciting and agreeable. He was hooked.

Kirkendall Phenomena and Sintering

In 1950, Bob's first position was as a researcher at the Sylvania Electric Company in Bayside, Queens, New York. The group he joined undertook basic materials research underpinning atomic energy production, funded by the Atomic Energy Commission (AEC). The Kirkendall effect, which was discovered in 1947, proved that diffusion in alloys does not occur by a direct exchange of different atoms. With Ben Alexander and Les Seigle, he carried out pioneering studies of Kirkendall phenomena, including the formation of porosity, dimensional changes, polygonization, and diffusion-induced recrystallization. They sintererd copper wires wound around a larger copper spool at high temperatures in a hydrogen atmosphere. They showed that both the bonding and the shrinking occurred primarily by volume diffusion, with the free surfaces and grain boundaries operating as sources and sinks. It was well known in powder metallurgy that sintering does not eliminate all porosity. This was explained for the first time by their research because the eventual loss of grain boundaries resulted in the cessation of shrinkage. All this research was supported by a superb team of metallographers, one of whom was Gloria Botway, whom Bob married in 1951. They would raise three children: Andrew, Barbara, and Frank.

Physics of Defects and Radiation Damage

In 1954, Tom Read was invited to head up an expanded and modernized Department of Mining and Metallurgical Engineering at the University of Illinois Urbana-Champaign. He invited Bob, Dave Lieberman, Marvin Metzger, and Howard Birnbaum to join him. Bob was thrilled to be offered the position of assistant professor in such a stimulating environment. Fred Seitz headed up the Department of Physics. Seitz was a pioneer of the physics of defects in crystals and of solid-state physics more generally. Seitz's vision was to build a modern metallurgy department engaged in teaching and research. He oversaw the establishment of a joint interdisciplinary research group, funded by the AEC and involving Fred Seitz and Jim Koehler from Physics and Charlie Wert and Bob from Metallurgy. The purpose of the group was to study crystal defects and radiation damage.

The next ten years were among the most exciting in the physics of crystal defects. Bob and his group achieved the following: (1) they determined the properties of vacancies and self-interstitials for the first time with considerable accuracy in several materials, (2) they revealed many of the defect processes associated with radiation damage, and (3) they measured self-diffusion coefficients with relatively high accuracy. Bob had a particularly fruitful collaboration with Ralph Simmons of the Department of Physics in which they measured equilibrium vacancy concentrations in aluminum, copper, and gold by simultaneously measuring length and lattice parameter changes during heating and cooling. These measurements enabled them to deduce the enthalpy and the vibrational entropy of formation of vacancies in these metals. These beautiful experiments pushed the limits of what was possible experimentally in the 1960s, and today they appear

in textbooks. They proved that vacancies are the dominant point defect in these face-centered cubic metals at thermodynamic equilibrium. Self-diffusion in these metals occurs by a vacancy mechanism. Other noteworthy collaborators included David Seidman on the kinetics of the formation of vacancies at dislocations, Fred Vook on radiation damage in germanium, Robb Thomson on dislocation climb, John Venables on migration of self-interstitials, Dick Siegel on vacancy annealing, and Art Ruoff on plastic strain enhanced diffusion.

Cornell University, 1964–78

Bob's move to Cornell University in 1964 was prompted in part by the building of a new Materials Science Center funded by the National Science Foundation and the modernizing and expansion of the Department of Materials Science. Cornell was already very strong in solid-state physics, and the Department of Engineering Physics was oriented towards materials physics. The move would also bring Bob and his wife closer to their families in New York State. Bob later described his time at Cornell as the happiest of his professional life. But in his personal life, he suffered a painful divorce from Gloria in 1969. In the early 1970s, he met Ruth Nickse, who was completing a Ph.D. in educational psychology at Cornell, and they married in 1974. Ruth had three children from a previous marriage: Stephen, Gail, and Robert.

With the financial support of the AEC and the Cornell Materials Science Center, Bob initiated a research program on ion radiation damage and point defects with the assistance of David Seidman and Dick Siegel, who had both moved with Bob from Illinois. This work led to electron microscope studies of radiation damage by displacement cascades (with Larry Thomas) and the establishment of a field-ion microscope facility led by David Seidman for the study of vacancies and divacancies and displacement cascades in irradiated metals. Bob was also involved in recruitment of personnel in the Department of Materials Science and Engineering and developing the academic curriculum. Walter Owen was recruited from the University of Liverpool to become the director of the newly expanded department, with a strong focus on the structure and properties of materials.

When Tilman Schober arrived from Germany, he and Bob began an electron microscope study of ion radiation damage. They were particularly interested in the defocusing effect of focused collision sequences caused by dislocations. They tried to produce thin-film specimens containing regular networks of dislocations, in the form of low-angle grain boundaries, by bonding single crystal films together face-to-face at small misorientations. They were successful and immediately realized this was a highly effective way to make thin-film bicrystal specimens containing grain boundaries with controlled geometries. This led them to carry out investigations of the intrinsic dislocation content of grain boundaries in which they systematically varied one of the five geometrical degrees of freedom, while keeping the remaining four constant. This work revolutionized the study of grain boundaries because (1) for the first time it was possible to manufacture grain boundaries with controlled geometries, (2) it became possible to correlate systematic changes in grain boundary structure with grain boundary geometry, and (3) these systematic experimental observations could be used to test theoretical predictions. Bob became so fascinated in the structure and properties of grain boundaries that he spent almost all his remaining research career working on them.

MIT, 1978–96

Ruth, Bob's wife, wanted to pursue a professional career in her field, but she was unable to find a suitable position in the small town of Ithaca. They decided to leave Ithaca for a large metropolitan area where there would be more openings. An opportunity arose in 1978 when a senior position opened in the Department of Materials Science and Engineering at MIT following the retirement of Michael Bever. Bob was allowed to bring most of his laboratory equipment from Cornell, and with the financial support of the U.S. Department of Energy he quickly got back into his research on grain boundaries. One of the attractions for Bob to return to his alma mater was to collaborate with John Cahn. They began joint research on diffusion-induced grain boundary migration that culminated in an important paper in 1981. Bob was disappointed when Cahn left MIT in 1979 to join the National Bureau of Standards (now the National Institute of Standards and Technology). Bob's research at MIT included electron microscopy of boundary structure, determination of boundary structure by X-ray diffraction and computer simulation, computer simulation of point defects in grain boundaries, grain boundary diffusion, grain boundaries as sources and sinks for point defects, grain boundary migration, and grain boundary phase transitions. The computer simulations were carried out by his long-standing collaborator Paul Bristowe, who had moved with Bob from Cornell.

Bob's prominence in the field of grain boundaries was recognized in 1978 when he chaired a Gordon Research Conference on them in New Hampshire. A year later, he chaired an American Society for Metals (ASM) Materials Science Seminar, entitled "Grain Boundary Structure and Kinetics," in Milwaukee, Wisconsin. These meetings were hugely successful, and they mark the coming of age of research on grain boundaries. They also cemented Bob's international reputation as a world leader in materials science.

In 1986, he was awarded a Humboldt Research Award from the Alexander von Humboldt Foundation, which

enabled him and Ruth to spend several months in Manfred Rühle's group at the Max Planck Institute for Metallurgy and Materials Science in Stuttgart. There he collaborated with Adrian Sutton, who was visiting Rühle's group at the same time. Geometric criteria for low energy interfaces had become popular, but it was not clear whether they were supported by experimental data. Their paper, published in 1987, demonstrated that a restricted form of only one criterion was able to predict low energy interfaces. The volume of research on interfaces had grown rapidly, and they recognized a need for a comprehensive, pedagogical book that spanned the subject in a coherent way. This led them to spend six years writing *Interfaces in Crystalline Materials*, which was published by Oxford University Press in 1995. It is Bob's most highly cited work, and it has had an enduring impact.

Teaching and Mentoring

Bob was a committed teacher who gave graduate courses on thermodynamics, phase transformations kinetics, crystal defects, theory of dislocations, diffusion, and physical metallurgy. His recognition of the importance of teaching is also evident in the three books he authored or co-authored. Bob was a great mentor and supporter of his students, postdocs, and colleagues. When he finished his term as chair of the Cornell Department of Materials Science and Engineering, he had more friends on the faculty than when he started.

Community Service

Bob served on review committees for various national laboratories and university departments of materials science. He was an organizer of national and international conferences on grain boundaries and other crystal defects. He also chaired several study groups for government agencies, notably the Department of Energy.

Retirement

Bob retired from MIT in 1996. Between 1995 and 2003, Bob and Adrian Sutton and their wives spent two weeks together each winter in Vieques, an island that is part of Puerto Rico in the Caribbean. Bob and Ruth fell in love with the island, and they bought a house there. Soon after Ruth died in 2003, Bob sold their beautiful house in Brookline (Boston) and moved back to Ithaca to be with his daughter Barbara. While there, he wrote two more books. The first, *Kinetics of Materials* (2005), was written with his MIT colleagues Sam Allen and Craig Carter. Bob wrote the second book, *Introduction to Elasticity Theory for Crystal Defects* (2012), by himself. The second edition of this book was published in 2016 by World Scientific when he was ninety-two years old. This is a remarkable pedagogical text treating inclusions, inhomogeneities, point defects, dislocations, and interfaces and their interactions in linear anisotropic elasticity. The theory is illustrated with many worked examples in isotropic elasticity.

Bob died at the age of ninety-eight at home in Ithaca, surrounded by his children.

Interests

Painting was an abiding passion. He was a member of the Cape Cod Art Association, the Cambridge Massachusetts Art Association, and several galleries, including one in Vieques. While he was at Cornell, he enjoyed taking his family out on his boat on Cayuga Lake. He was a secular humanist, an ardent supporter of the Establishment Clause of the First Amendment, and a proponent of the scientific method. He said he became addicted to jazz in his high school days and played the trumpet in a dance band called The Techtonions when he entered MIT in 1941. He discovered classical music when LPs were first issued, preferring concertos and chamber music to symphonic music and operas. His greatest musical love was the late chamber music of Beethoven and Schubert. Holidays in Vieques were filled with painting, swimming in the warm seas of the Caribbean, and listening to Schubert's late piano sonatas played by Mitsuko Uchida. At the end of his life, he was greatly concerned and angered by the failure of political leaders to recognize and adequately respond to the colossal oncoming catastrophe of global warming caused by the burning of fossil fuels. He was also deeply distressed by the state of U.S. politics.

Awards and Honors

Bob earned many honors throughout his career. He was a Fellow of the American Physical Society; the Minerals, Metals & Materials Society; and the American Academy of Arts and Sciences and a member of the National Academy of Sciences. He was awarded the R. F. Mehl Gold Medal from the American Institute of Mining, Metallurgical and Petroleum Engineers (1982); the Acta Metallurgica Gold Medal from Acta Materialia Inc. (1987); the Fellowship Award from the Japan Society for the Promotion of Science (1987); and the Von Hippel Award from the Materials Research Society (1990). He was named a Senior Scientist by the Alexander von Humboldt Society (1986). He was awarded the David Adler Lectureship by the American Physical Society (1989); the Peter G. Winchell Memorial Lecturer at Purdue University (1990); the Van Horn Distinguished Lectureship at Case Western Reserve University (1992); the Thomas Read Memorial Lecturer at the University of Illinois at Champaign-Urbana (1992); and the Herbert Johnson Memorial Lecturer at Cornell University (1992). The Materials Research Society held a symposium in his honor at the organization's 1993 fall meeting, and the Journal of Physics and Chemistry of Solids published a festschrift in his honor in October 1994 (Volume

55, Issue 10). Northwestern University awarded him an honorary doctorate in 1999.

Acknowledgments

Much of this memoir was taken from the autobiography Bob wrote for his Festschrift published in 1994. I have also used the obituary he wrote about himself in October 2019 that was published in the *Ithaca Journal* shortly after his death in 2022. I am grateful to David Seidman, Dick Siegel, and Paul Bristowe for their comments on an earlier draft.

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