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Robert L. Coble: A Retrospective

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The purpose of science is to create opportunities for unpredictable things to happen.
Freeman Dyson

This issue of the *Journal of the American Ceramic Society* is dedicated to Robert L. Coble, an innovator in both the theory and practice of ceramic science, who died on August 27, 1992, at the age of 64. To many materials scientists, many fundamental principles of materials science, including the concepts of mass transport by diffusion during sintering, phase transformations, and creep and transport along different diffusion paths, are accepted facts, handed down from antiquity. In reviewing the life of Coble we are reminded that the development of materials science as a discipline is recent and that Professor Coble was critical in making the connections between seemingly different processes, independent of type of material, and in establishing a theoretical and experimental basis for what we have come to think of as modern "materials science." By dedicating this issue on the "Science of Alumina" to him, we recognize Coble's fundamental contributions to ceramic science, his inspiration of several generations of graduate students, and his abiding fascination with everything to do with alumina.

A native of rural Pennsylvania, Robert Coble began graduate school in 1950 in the Massachusetts Institute of Technology ceramics program with a bachelor's degree in physics from Bethany College, following a two-year stint as a paratrooper in the U.S. Army. Legend has it that he arrived at MIT for his first day in graduate school still clad in his Army fatigues.

World War II had helped to precipitate a change in materials science that was reflected in the graduate ceramics program at MIT. F.-H. Norton, the head of the MIT ceramics program, had been involved in the production of oxide refractories required for the purification of uranium oxide and plutonium oxide. After the War, the Atomic Energy Commission continued to fund his basic work on oxides, a marked departure from the pre-war clay-based ceramics program. As a member of this expanding program, Coble displayed the traits by which he was later known: he was bright, charming, irreverent, immensely curious, and had great intuition for the important problems. In 1955, he finished his Ph.D. as one of W. D. Kingery's first students, with a thesis on the mechanical properties of porous alumina. With this Ph.D. research began his life's work on structure–property relationships of materials, especially ceramics.

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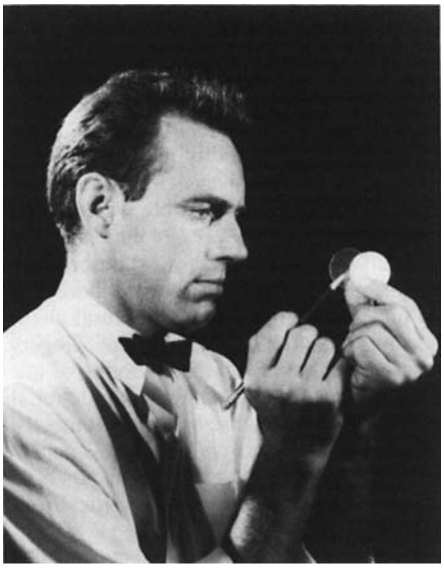

Robert L. Coble (Photograph courtesy of The MIT Museum).

In 1955, Coble joined the General Electric Research Laboratories. In those days the notion that major industries should support research on fundamental problems at "campuslike" laboratories was ascendant. Joe Burke, who had been at Cyril Stanley Smith's Institute for the Study of Metals at the University of Chicago, put together GE's ceramics group, including Coble, R. E. Carter, R. J. Charles, M. L. Kronberg, S. P. Mitoff, and W. H. Rhodes; Dave Kingery collaborated with this group as a consultant to GE. Dave Turnbull assembled the metallurgy counterpart, containing J. W. Cahn, R. H. Doremus, E. W. Hart, J. E. Hilliard, W. B. Hillig, J. S. Kasper, and R. A. Oriani; F. C. Frank served as a consultant to this group. These two groups worked closely with other GE materials scientists, including K. T. Aust, J. C. Fisher, J. J. Gilman, J. W. Rutter, R. A. Swalin, and J. H. Westbrook.

The interaction between ceramists and metallurgists brought forth a whole new set of concepts and research tools to analyze ceramic microstructures, even including the way ceramists looked at their materials. Before World War II, ceramic microstructures had more in common with geologic specimens than with the fine-grained materials we think of as polycrystalline ceramics. Ceramics were typically multiphase, large-grained, usually porous, refractory materials, examined using petrographic thin sections for which the thickness of the section was smaller than the grain size of the ceramic. Through his interactions with Smith and Clarence Zener in Chicago, Burke found that many of the features being discovered in metal microstructures were observable in ceramics using metallographic polished sections instead of thin sections. With this better view of grain boundaries and other microstructural features, obtaining an understanding of the high-temperature kinetics processes that controlled microstructure evolution became a reasonable goal for the GE ceramics group.

According to a GE report written the year Coble joined the company, the specific charter of Burke's Ceramics Studies section was to "look for answers to the question, 'How does the structure—that is, the composition, crystal structure, and microstructure—develop under various conditions, and what are the relations between this structure and the mechanical, magnetic, electrical, and optical behavior of materials?' The systematic approach on which (the metals group) base their studies has led over the past 25 years to striking results in the field of metals, but is something new to the study of ceramics." (GE Metals and Ceramics Report, 1955, p. 9.)

This approach and the interaction among ceramists and metallurgists led to a host of scientific and technological discoveries. As an active member of the Metals and Ceramics Research Department, Coble flourished in this stimulating scientific atmosphere and latched on to the idea of using additives to change the degree of attachment of pores to grain boundaries. The notion of Zener pinning of grain boundaries had gained greater credibility when manganese sulfide particles were found to be the critical element in controlling the grain size in the important GE iron–silicon alloy used for transformers. Likewise for ceramics, the discovery (by Coble and Burke) that pores in ceramics could pin grain boundaries or could be dropped by grain boundaries and entrapped within the grains, depending on the processing and chemistry, was important in understanding sintering. Since pores dropped from boundaries virtually stopped shrinking, slowing down grain-boundary motion so that pores could keep attached became an important working strategy.

Out of this work came one of the most important discoveries to ceramists and to GE: Coble's invention in 1957 of adding small amounts of magnesia to alumina to allow it to sinter to theoretical density without pores becoming entrapped within grains and without the concomitant abnormal grain growth. Suddenly the impossible was possible: alumina densified fully, all pores remained attached to grain boundaries during sintering, and the grain size remained small and uniform. This process to make dense alumina, called Lucalox® by GE, made possible the production of high-pressure sodium-vapor lamps for highway illumination. For this invention, Coble was awarded the National Institute of Ceramic Engineers' Professional Achievement Award in 1960.

Coble's technological achievement inspired the ceramics community to expect better microstructures in many materials and triggered considerable innovative scientific research on the mechanisms of sintering and grain growth over the following 35 years. The idea of dopant additions being effective in concert with the emergence of hot pressing as a viable technique led to the expectation that a fine-grained, dense microstructure should be attainable for virtually any ceramic or refractory material. Such was reflected in the fabrication of high-density silicon nitride, initially by hot-pressing in England, and then silicon carbide, by sintering; the latter was discovered in 1975 by Svante Prochazka, a former Coble student, then at GE. This work plus that of others, including Coble and former MIT students W. H. Rhodes and R. E. Mistler, reinforced the slowly emerging concept that, for any material, high density should be attainable by pressureless sintering with the use of the proper dopant and sintering atmosphere and with good submicrometer powder. Similar advances followed for electrical and functional ceramics. In addition, the mechanisms leading to the changes in alumina microstructures with the addition of magnesia have been long studied and debated. In the book, *Sintering of Advanced Ceramics*, dedicated to Coble for his 60th birthday in 1988, Martin Harmer cited over 70 papers in which the authors aimed to unravel the mystery of what magnesia does to expedite the sintering of alumina. These revealed many interesting phenomena, but also seemed to largely confirm Coble's early intuition that inhibition of boundary migration by solute drag was the predominant factor in producing high-density alumina.

In 1960, Coble rejoined Kingery at MIT, this time as an assistant professor of ceramics in the metallurgy department. Here again there was a vision of establishing the foundations of physical ceramics and processing science. This successful collaboration between Coble and Kingery continued with funding from the U.S. Department of Energy and its predecessor agencies (AEC and ERDA) for over 25 years. The academic group grew to a peak of seven faculty members, plus staff, students, and stimulating visitors. Coble became an associate professor in 1962, received tenure in 1966, was named a full professor in 1969, and was granted emeritus status when he retired in 1988. During his 28 years on the MIT faculty, Coble was the thesis advisor for 24 masters degree students, 43 Ph.D./Sc.D. students, and coadvised many others. He published over 114 papers.

At MIT, Coble established his reputation for deriving proper theoretical descriptions of mass transport during sintering and creep and for understanding the relationships among various processes. In terms of both ceramic science and engineering, Coble's greatest achievements were in his contributions to the understanding of microstructural changes during sintering. Equally important to the advancement of ceramic science was Coble's commitment, along with that of Kingery, to doing all the measurements necessary for critical and quantitative tests of theory. Coble's seminal papers on the modeling of intermediate- and final-stage sintering, hot-pressing, and creep by grain-boundary diffusion are classic works which helped to define the field. These, especially the creep paper, his most cited, were also crucial to understanding the high-temperature behavior of metals. Coble received the Ross Coffin Purdy Award from the American Ceramic Society in 1970 for his *Journal of Applied Physics* paper on the relationship between sintering and hot-pressing. This clearly showed the similarity in the diffusional transport that occurs between pores and grain boundaries in response to external and capillary forces. His theoretical and experimental work on the critical steps in the sintering process is summarized in the classic paper, "Current Paradigms of Ceramic Powder Processing."

Coble's contribution to ceramic science goes well beyond the simple aspects of solid-state sintering. He recognized early the importance of liquid-phase sintering, enhanced sintering below the eutectic, chemical reactions during sintering, and diffusion-induced grain-boundary migration. He also addressed the effects of particle-size distributions on differential densification and internal stress generation. He was a pioneer in promoting composition control in ceramics for basic science research. For example, effects of small compositional changes on the structure and composition of grain boundaries in alumina were identified by P. A. Morris and Coble.

Fluorescence measurements of internal stress in alumina were first performed by J. E. Blendell and Coble and were recently developed by D. R. Clarke and co-workers into a precise technique for measuring the stress in individual grains.

Finally, Coble illustrated his breadth and his propensity for conceiving clever experiments in the study of electrical conductivity and electronic structure of alumina. Using an innovative tubular sample design, K. Kitazawa and Coble measured the electrical conductivity and transference numbers more precisely than was then common; this revealed the conductivity to be electronic rather than ionic over a wider range of conditions than expected. This discovery then motivated the subsequent development by J. B. Blum, R. H. French, and Coble of techniques to measure the optical reflectivity at unprecedentedly high temperatures from which much about the electronic structure and its temperature dependence has been deduced for wide-band-gap oxides.

In addition to Bob Coble's public contributions to ceramic science, he inspired several generations of students and colleagues by his dedication to ceramic science, enthusiasm for research, ability to isolate the fundamental issues in many complex problems, and unassuming attitude toward both people and science. Coble's research style was well suited to the MIT academic environment. He enjoyed interacting with students and colleagues, both scientifically and socially. His favorite interactions were with graduate students, where he took great joy in challenging and inspiring students with important, unanswered problems or in being similarly challenged. In fact, problems for which the solutions were known held little interest for him. Personal glory was of no importance to Coble. His philosophy was that nature presented a wealth of puzzles, and, if someone solved one problem before he could find the answer, he was glad to know the solution so he could go on to another, equally interesting problem. Above all, he was interested in knowing scientific truths, much more than in having personally been the discoverer of these truths.

While maintaining high standards for scholarship, he also believed that recreation and friendship were important parts of life. In a letter of support for his promotion to associate professor, an external reviewer wrote, "In his undergraduate work at Bethany College he received superior marks in the physics course offered, while keeping a very active social schedule." This was a key part of Coble's character, both in the laboratory and out. Coble and his wife, Joan, enriched the lives of graduate students through innumerable Vermont skiing weekends and picnics at their home. Through the combined efforts of Coble, others on the MIT faculty, and the laboratory manager, Pat Kearney, the students received critical help needed for their experiments as well as a sense of community from all different types of interactions, from coffee breaks to monthly in-laboratory hot-dog roasts.

Coble was the recipient of many lectureships, prizes, and other external awards, but these by no means fully indicate the legacies he left to ceramic science and engineering. He was made a member of the National Academy of Engineering in 1978, and he received a prestigious Humbolt Stiftung award in 1984 that permitted him to study at the Max Planck Institute in Stuttgart, Germany. His legacy, of course, includes many people in both academia and industry throughout the United States and several other countries, whose creativity and standards for scholarship were, at least in part, inspired by Coble as students or colleagues. Finally, his instincts for good problems and honest reporting are revealed in the many ongoing research topics on which he instigated work. The cover of this edition of the *Journal* shows the "Morris" grain boundary that was grown at MIT by a float zone technique, under the inspiration of Coble and the aid of John Haggerty, and recently analyzed by high-resolution TEM and modeled in unexpected detail by the MPI group in Stuttgart, under M. Ruhle, as reported in three different papers at the 1993 Schloss Ringberg meeting. That meeting also had presentations on many of the same topics discussed above, of course including one on the role of magnesia in inhibiting abnormal grain growth.

Finally, Coble's papers, like his conversations, were not always easy to understand: he assumed that the reader/listener could clearly see the same dichotomy that he saw between what was "understood" about a process and what experiment told him. Time and again, it needed Bob Coble to see what others failed to see. He spoke joyfully with his students about "serendipity," defined by Webster's Dictionary as "the faculty of finding valuable or agreeable things not sought for." Coble had this amazing gift. To the end, he advised his students and colleagues to delve into some area that he had just learned about but did not understand because he knew, somehow, it would be important to them. His papers remain full of important, still unrecognized connections and insights, and serve as a legacy to future generations who did not have the opportunity of knowing the man himself.

Acknowledgments

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