Anthony G. Evans

1942-2009

BIOGRAPHICAL *Memoirs*

A Biographical Memoir by John W. Hutchinson

NATIONAL ACADEMY OF SCIENCES

ANTHONY GLYN EVANS

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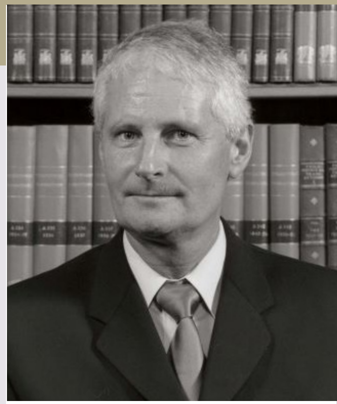

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By John W. Hutchinson

Anthony Glyn Evans was one of the leading scientists of his generation in the field of materials. He worked during a period in which materials development and application emerged as central to many technological advances and materials science came into its own as an area of research and application. This memoir describes Evans' remarkable influence and contribution to materials science and more broadly to engineering science. Evans had no rival when it came to the grasp of the underlying fundamentals of material behavior coupled with an extraordinary ability to focus his attention and to inspire and lead collaborative efforts. Evans brought people together, and he brought out the best in people. His productivity was prodigious, with well over six hundred technical papers to his credit. Over the course of his career, he collaborated with more than four hundred individual co-authors. At the time of his death, Evans was the most highly cited materials scientist, and he continues to be one of the most cited more than ten years later. A short list of subjects to which Evans made major contributions includes the exploration of virtually all aspects of the thermo-mechanical behavior of advanced ceramics, ceramic-matrix and metal-matrix composites, thin film mechanics, interface fracture, thermal barrier coatings, metallic foams, morphing structures, aerospace materials for high temperature applications, lightweight lattice materials, and the design of materials and structures for resistance to blast and ballistic impact.

Anthony G. Evans was born and raised in Porthcawl, Wales. His parents were William Glyn and Annie May Evans. He attended the local Bridgend Boys Grammar School. In 1961, Tony, as he was known to all, matriculated at Imperial College in London, reading metallurgy and graduating in 1964 with a bachelor of science degree with first class honors. That same year, Tony married Trisha Cross, whom he had met in Porthcawl. He continued at Imperial College and enrolled in the Ph.D. program in metallurgy. His Ph.D. thesis dealt with dislocation motion and plasticity in a single crystal material, calcium fluoride, work that was subsequently published jointly with this thesis supervisor, Peter L. Pratt.[1] This launched his career into one of his lifelong areas of interest, ceramic materials. Evans' thesis, which he finished in 1967, was awarded the Matthey Prize.

Early Research on the Mechanical Behavior of Ceramics

The mid-1960s was the period when interactions between material scientists and mechanics researchers began to escalate, not only in the development and application of fracture mechanics but across the entire field of engineering materials. From its start, Evans' career personified this interaction. Educated as a material scientist, he increasingly expanded his expertise by making use of experimental and theoretical methods drawn from mechanics and by working directly with researchers in academia and industry trained in mechanics. As his career progressed, Evans' exceptional breadth and talent as a research leader grew, his engineering skills emerged, and he extended his interactions to include chemists and physicists interested in the thermo-mechanical behavior and applications of materials.

After obtaining his doctorate, Evans began work in 1967 as a ceramist at the Atomic Energy Research Establishment near Harwell, Oxfordshire, where his first papers focused on the strength and fracture of ceramic materials of emerging technical importance such as aluminum oxide, magnesium oxide, silicon nitride and uranium oxide. Several of the papers during his time at Harwell were co-authored with the head of the ceramics group, Roger W. Davidge. A major emphasis was the high-temperature mechanical behavior of ceramic materials relevant to the generation of power from nuclear reactors.[2] As would be the case throughout his career, Evans employed theory to understand the underlying fundamentals of the material behavior and to design the experiments that he and his co-workers performed to measure material behavior as well as to observe new phenomena. It was during his time at Harwell that Evans began making use of fracture mechanics to characterize the toughness of brittle ceramic materials,[3] an activity he pursued in many forms his entire career and for which he became a leading expert. These were the early days of fracture mechanics, the development of which as a tool for characterizing engineering materials and analyzing structural failure had only been underway for about a decade.

Moving to the United States

Evans spent a sabbatical year at the University of California in Los Angles in 1970 and then returned to Harwell. Not long after, however, he accepted a position at the National Bureau of Standards (later renamed the National Institute of Science and Technology) in

Gaithersburg, Maryland, and moved to the United States with his family. At the Bureau, Evans expanded the scope of his prior research in ceramics in several directions, including slow stable crack growth in polycrystalline ceramics under cyclic loading and at high temperatures, impact damage, and the use of statistical methods to characterize fracture. He and his colleagues employed acoustic emission as a tool to study crack advance in ceramics, and he published some of his first papers laying out the fundamentals of fracture of brittle materials and its applications, including experimental techniques for measuring fracture toughness, as it is usually called in the fracture community.

It was during this period that Evans and several colleagues at the Bureau, including Sheldon M. Wiederhorn, wrote several influential papers on the fracture of brittle materials, including glass;[4] one application concerned the design of space shuttle windows. Because of the difficulty of preparing standard test specimens for measuring the fracture toughness of structural ceramics, Evans promoted the use of indentation techniques, which, together with crack analysis, permitted the experimentalist to measure fracture toughness in terms of the observed length of the cracks emanating from the indentation. In 1974, he moved to the Rockwell International Science Center in Thousand Oaks, California, where he served as a group leader until 1978. During his time at the Bureau and at the Rockwell Science Center, Evans wrote a series of papers on the indentation technique, including contributions with Brian R. Lawn and David B. Marshall;[5] he would have many collaborations with Marshall in the years to come.

University of California, Berkeley

Evans' exceptional productivity and breadth of scientific interests displayed in the decade after obtaining his Ph.D. established him as an up-and-coming leader in the field of structural materials. At Rockwell, he served as group leader for Ceramic Materials and principal scientist in Structural Materials. It was during this period that his lifelong active association with the American Ceramic Society began. Also in 1974, Evans began a remarkable engagement as a member of the Materials Research Council (later renamed the Defense Science Research Council) that would last until his death. The Materials Research Council, comprising a group of roughly two dozen engineers and scientists drawn from academia, industry, and government labs, interacted with the leadership and program managers of the Defense Advanced Project Research Agency (DARPA) of the U.S. government to identify and initiate research on promising new opportunities in materials. In the 1970s and 1980s, this group was primarily composed of material scientists, chemists, physicists, and mechanics specialists, reflecting the breadth of colleagues with whom Evans would develop scientific associations.

In 1978, Evans was recruited to join the faculty of the Department of Materials Science and Mineral Engineering at the University of California, Berkeley, (Berkeley) where he continued to expand the scope of his studies in ceramics materials. He launched fundamental studies of the process of sintering of ceramic powders used to produce high-performance polycrystalline forms of the materials. He conducted experimental and theoretical investigations of the erosion of ceramics by the impact of water droplets. At Berkeley, Evans initiated what would turn out to be one of his many lifelong interests—toughening mechanisms in structural ceramics, such as stress-driven martensitic transformations and crack deflection at the microstructural level.[6,7,8] He also made his first research forays into ceramic matrix composites reinforced by ceramic fibers and metal matrix composites reinforced by ceramic particles.[9] For the first time, Evans ventured into studies of wear and the fracture and adhesion of ceramic coatings and thin films. In the ensuing years, Evans, his students, and his collaborators would make major contributions in all these areas.

Evans' legendary skills for intuiting important research areas and for gathering, and leading, collaborators became apparent during his days as a young faculty member at Berkeley. His early work on martensitic transformations in partially stabilized zirconia[10] with his Berkeley colleague, Rowland M. Cannon, and Arthur H. Heuer of Case Western Reserve University set the stage for a significant advance in understanding of transformation toughening in ceramics. Not long after, Evans and Robert M. McMeeking, a specialist in solid mechanics at the University of Illinois at the time, contributed to that advance through their detailed modeling of the role played by transformation triggered by the high stress at the tip of a crack.[11] As the crack tip advances into the zone of transformed material it has triggered, the stresses are lowered by the strains induced by the transformation, somewhat akin to the role of plasticity in ductile materials. Evans' early research on the mechanical performance of thin brittle films and coatings was conducted with numerous researchers including Marshall and Brian N. Cox, former colleagues at Rockwell. This was another subject area to which Evans would contribute throughout his career. Two of Evans' graduate students from the Berkeley days went on to make their own marks in materials engineering: Katherine T. Faber, who studied toughening by the mechanism of crack deflection, and Michael D. Thouless, who investigated the role of void growth and grain boundary cavitation in high temperature creep failure of structural ceramics.

University of California, Santa Barbara

In 1985, Tony Evans moved to the University of California at Santa Barbara (UCSB) to become the Alcoa Professor and founding chair of the newly created Department of Materials. He was also appointed to co-direct the Center for High Performance Composites lodged within this department. During his six-year tenure as departmental chair, Evans, in collaboration with the Dean of Engineering at UCSB at the time, Robert Mehrabian, hired many new faculty members who in a relatively few years would elevate the materials department at UCSB to one of the leading departments of materials in the world. Simultaneously, Evans' research activities flourished as never before. Indeed, his collaborators from outside UCSB, of which the author of this memoir was one of many, were largely unaware that Evans had the responsibility of being a department head. When quizzed as to how he could maintain such a full plate of research and at the same time develop and chair a major department, Evans said he had let it be known from the start that he only dealt with departmental duties between 7 a.m. and 9 a.m. in the morning. This enabled him to focus his attention on administrative tasks for a limited time and had the beneficial side effect of discouraging at least some of the usual frivolous departmental matters.

The ability to focus his attention intensely on any task at any time of the day was one of Evans' remarkable attributes. Colleagues who travelled with Evans on long flights to technical meetings marveled at how he could work on preparing a talk or writing a paper late into the night while everyone else on the plane would be sleeping or trying to do so. A common joke among his colleagues was "another cross-country flight for Evans, another paper." An individual with Evans' breadth of interests and energetic approach to technology could not escape the attention of the leaders of research and development departments at technical companies. By this time, he was consulting for a growing number of companies in structural ceramics, aerospace, and electronics. It was often said that Evans never encountered a challenging problem that he did not like nor could resist. His consulting experiences motivated much of his academic research. His early work on thin film failures, such as delamination and cracking, was motivated by issues he encountered when consulting for companies producing electronic packages for powerful computers. Consulting for jet engine producers in Europe and the United States led to Evans' initial investigations into the failure mechanisms limiting the durability of thermal barrier coatings (TBCs). These are the ceramic coatings that had been employed beginning around 1990 on the surface of blades and other metallic components in the hottest sections of jet engines, of which more will be said later. His consulting for a manufacturer of ceramic bricks used in the construction of the large high-temperature furnaces for melting metals and glasses even led Evans to investigate technical cost modeling of the highly specialized, and costly, furnaces used to produce the bricks themselves.

Not only did industrial consulting take Evans to companies, Evans brought industrial technology developers to workshops at UCSB that he organized and chaired. Starting not long after his arrival at UCSB in 1988, Evans launched an annual three- or four-day January workshop called the Winter Study Group that focused on a major research topic. Within only a few years, these workshops became a big draw for industrial and academic researchers in the United States and abroad, and for many one of the scientific high points of the year. Multiple years were devoted to most of the research topics of focus, such that progress year by year could be assessed. The first round of workshops, held annually for about five years, addressed ceramic composites. Workshops on thermal barrier coatings, metal foams and lattice materials, and other topics would follow. Evans drew on the help of senior colleagues at UCSB, such as David R. Clarke, Fred F. Lange, Frederick A. Leckie, Carlos G. Levi and Frank W. Zok, to organize the workshops and to identify invitees for specialized sessions. Evans' intimate knowledge of, and active involvement in, every aspect of the scientific and technological issues discussed at these workshops is what made them so successful. With his low-key, genial manner, Evans was able to tease out communication across industrial and academic lines, and it was Evans who ensured that critical problem areas were identified and pursued in the coming year. The wisdom of the funding agencies willing to support the research and the workshops must also be acknowledged, particularly the Office of Naval Research, one of the primary supporters of Evans' research and the Study Groups over many years.

It was not all work and no play at the workshops. Tony and his wife, Trisha, always hosted a party at their home that brought the participants together at the end of a long day of discussion and presentations. California wine and talk flowed freely. These were memorable occasions. Usually, on one of the other evenings, the visiting participants would be invited by the UCSB graduate students to one of their favorite venues for a more informal gathering. Both events contributed to the larger purpose of the workshops. Mention must be made of some the "regulars" from outside UCSB who participated in the Study Groups over the course of many years. They came from many countries, including Australia, France, Germany, Japan, and the UK. From academia, there were M. F. Ashby, B. Budiansky, V. S. Desphande, N. A. Fleck, M. Y. He, A. H. Heuer, Y. Kagawa, M. Ruhle, S. Sampath, H. N. D. Wadley, and the author of this memoir.

From industry, there were B. N. Cox, D. B. Marshall, R. Darolia, C. M. Johnson, D. M. Lipkin, M. Maloney, R. Naslain, J. Nichols, M. Oechsner and J. C. Williams. Colleagues who participated in these workshops have retrospectively expressed the view that the Study Group represented an exceptional model of how to conduct research in new technological areas. The difficulty with such a model is that it requires an Evans to make it work.

The first five-year set of Winter Study Groups on ceramic composites had a primary emphasis on composites with ceramic matrices reinforced by ceramic fibers (CMCs), but attention was also given to metal matrix composites reinforced by ceramic particles. The high melting temperature of ceramic materials makes them obvious candidates for applications in furnaces and jet and power generating turbines, which reach temperatures well above those for which metals remain viable. Their use as furnace liners where structural function is not important, or minimal, goes back centuries. The replacement of metal components in jet engines and power-generating turbines with ceramics has been a holy grail for decades and remains so today. The desirable high temperature characteristics of ceramics is offset by their brittleness, however, and this characteristic has hindered their adoption for applications in which structural strength matters. It has long been appreciated that one way to increase the toughness of CMCs is to use high-strength ceramic fibers to reinforce the ceramic matrix. Equally important, to ensure that cracks initiated in the matrix do not propagate into the fibers, the composite must be designed such that the matrix cracks deflect into the fiber-matrix interface, causing the fiber to debond from the matrix and slide relative to the matrix. Ultimately the fibers do fail but not at the matrix fracture plane, such that the energy dissipated in the debonding and frictional sliding of the fibers, referred to as fiber pullout, adds enormously to the toughness of the composite material.[12]

In collaboration with B. Budiansky and the author of this memoir, Evans wrote one of the foundational papers on the role of fiber debonding and pullout in the toughening of CMCs.[13] There are many challenges to designing composites with these characteristics, not the least of which is that the high temperatures at which they are expected to operate tends to enhance fiber-matrix interface bonding and thereby eliminates the toughness eancement.

Anticipating the breadth of scientific problems that would be encountered, Evans put together a group of individuals for the CMC Study Group drawn from materials science, mechanics, and chemistry. Over the course of the five years that the CMC Study Group met, the scientific foundations for CMCs and other composite systems were laid.[14,15,16] The mechanics of interface fracture was developed and applied to ceramic-ceramic and ceramic-metal interfaces. The concept of a mode-dependent interface toughness emerged and was quantified characterizing different combinations of tension and shear that act on the interface depending on how a component is loaded. New experimental test methods for measuring mode-dependent interface toughness were invented, and toughness data for various interfaces of technological interest were gathered. Fiber coatings with chemical compositions designed to ensure the fiber-matrix interface would continue to debond and slide even after many high temperature cycles were developed.

Despite the foundational advances, and even with the active collaboration of industrial researchers, significant implementation of CMCs in jet and gas turbines did not occur in the 1990s. It took more than a decade for implementation of CMCs to begin to take off. At the time of this writing, manufacturers are pushing hard to implement these new composite materials in the hottest sections of the engines. Evans' scientific contributions and leadership contributed greatly to these developments. The interface mechanics developed under the stimulation of the Study Group turned out to have many applications, including the delamination and spalling of thin films and coatings and the interface failure of multilayered systems, such as those used in electronic packaging. Evans and his collaborators had a hand in developing many of these extensions through their experimental and modeling studies of specific material systems. Some of his earliest efforts in this area were carried out in collaboration with students, such as Michael D. Drory, Mason S. Hu, Michael Thouless, and Tao Ye, and a young faculty colleague at UCSB, Zhigang Suo.[17,18] Through consulting, Evans spread the word of the utility of the methods to companies. Interface fracture mechanics would feature prominently in the second five-year Winter Study Group series devoted to thermal barrier coatings.

Ceramic thermal barrier coatings (TBCs) are a remarkably sophisticated creation of materials scientists. Since the time roughly three decades ago when they were first adopted by the aircraft industry, TBCs have been deployed throughout the hottest sections of aircraft engines. They were adopted as coatings in power generating turbine engines somewhat later. In combination with internal or back surface cooling of superalloy components, the coatings provide thermal insulation and environmental protection of blades, combustors and shell walls enabling gas temperatures that can exceed the melting temperatures of the metal superalloys. Because of the crucial role played by TBCs, research on extending their durability and thermal capabilities has been underway since their initial deployment. As a materials scientist, Evans assumed a leadership role in TBC research by reaching out to members of the mechanics community for help in understanding and characterizing coating failure mechanisms, which include cracking, delamination, and spalling driven by the extreme thermal cycles the components experience. The TBC activity developed into the second major Winter Study Group.

The scope of the efforts of the TBC Study Group was broad, spanning the relevant properties of coating materials, such as thermal conductivity, phase stability, and oxidation resistance, as well as the failure mechanisms limiting coating durability. TBCs are multilayers (see Figure 1) with the ceramic thermal barrier layer on top and a metallic bond coat (typically an alloy of aluminum) bonded to the superalloy substrate. A thin ceramic layer, called the thermally grown oxide (TGO, such as aluminum oxide), develops and thickens at the top surface of the bond coat as it becomes oxidized at high temperatures. The coating depicted in the illustration is representative of those on the blades of jet engines. Electron beam deposition is used to create the top thermal barrier layer, typically an Yttria-stabilized Zirconia with a columnar single crystal structure. The illustration shown here is one of the many iconic figures that

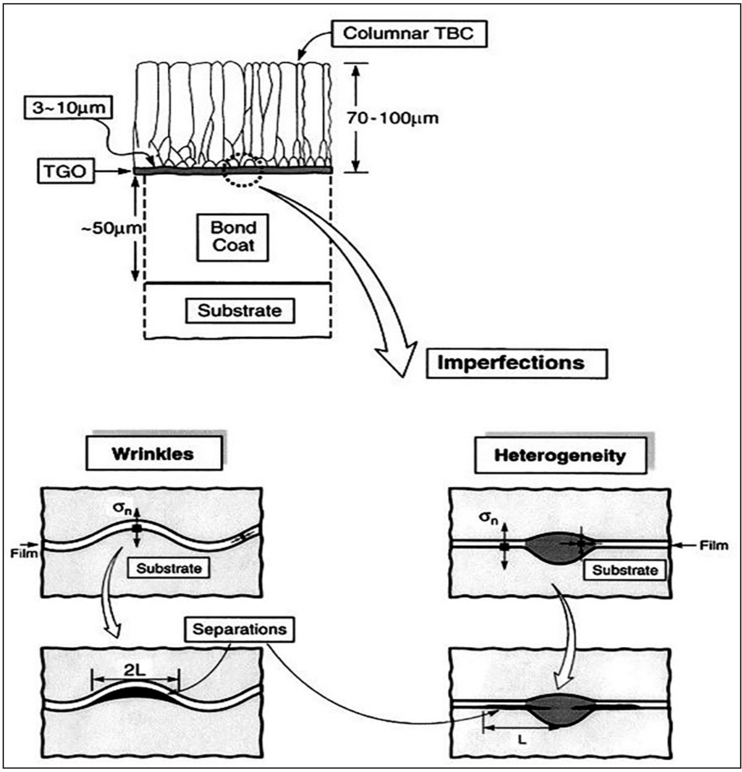

Figure 1: A sketch of an electron beam deposited thermal barrier coating representative of those deployed on turbine blades and other surfaces in the hottest sections of jet engines, including illustrations of flaws that can trigger coating delamination, as composed by A. G. Evans.[19]

Evans produced for this and other studies that helped define the outstanding issues in the field.[19] He worked closely with a graphic artist, iterating back and forth until he felt the message conveyed by the figure was clear. In addition, he refined these figures in subsequent publications to further embellish the message.

The description above conveys the complexity of a TBC. In a thermal cycle of a commercial aircraft engine, consisting of take-off, cruising and landing, the hottest section of the engine experiences temperature changes of well over 1,000 degrees Centigrade. Moreover, the engine is subject to this cycle thousands of times before the engines are overhauled and the coatings are renewed. Coating durability is essential and, moreover, because of the ongoing push for higher engine operating temperatures, is continually being challenged. Large thermal stresses develop in the layers of the TBC as a result of the differences in the thermal expansion properties of the individual layers and the superalloy substrate. The multilayer must be designed to tolerate these stresses. The columnar structure of the top ceramic thermal barrier layer is designed to have a high in-plane compliance (low elastic modulus) to keep the stresses as low as possible. As an aside, the top layer of the TBCs employed in gas-powered generating turbines, where the blades are much larger, are thicker and deposited by a plasma spray process that creates a porous, polycrystalline ceramic layer containing a high density of fine cracks and provides the requisite compliance.

One of the most common failure modes of the coatings is delamination cracking either at one of the TGO interfaces, triggered by flaws such as interface undulations or heterogeneities, as seen in the illustration, or in the top ceramic coating just above its interface with the TGO. The largest stresses in the coating are compressive and occur when the engine is cold. At the highest temperatures, the stresses tend to relax owing to thermal-creep processes in the coating, and then during cooldown the larger thermal contraction of the metal substrate relative to that of the ceramic coating generates compressive stress. The compressive stress results in a failure mode known as buckling delamination in which the coating buckles as the delamination crack spreads and ultimately the coating spalls off the substrate.

The preceding paragraphs only begin to give an overview of some of the thermo-mechanical issues involved in the Study Group's efforts to improve TBCs. As usual, Evans was at the center of these efforts, driving both experimental and modeling efforts to gain a clearer understanding of performance and failure mechanisms, as well as promoting the development of test methods to measure relevant material properties. He had able assistance from his UCSB colleagues. For example, Clarke, with collaborator Vladimir K. Tolpygo, carried out a major series of experiments on TBC failure modes, and Levi became one of the most knowledgeable experts on the huge set of thermo-mechanical material properties relevant to TBCs. Interface integrity of multilayer coatings is a critical aspect of their durability. Evans and his collaborators worked to develop test methods for measuring the toughness of the critical interfaces in the TBC, which is challenging because of the brittleness of the materials themselves. He encouraged teams represented at the Study Group from France, Germany, and Japan to pursue their own toughness measuring methods and to generate independent data.

As in the earlier CMC Study Group, there was extensive involvement from industrial participants providing essential technological motivation and direction. The TBC Winter Study Group was also funded by the Office of Naval Research, and it met annually for five years, followed by subsequent workshops devoted to TBCs that met every second or third year. At least one of these workshops took place after Evans' death. For his part, Evans worked on TBCs for more than twenty-five years, right up to the time of his death.

The Study Groups constituted only a small fraction of Evans' time and effort. During this first period at UCSB, from 1985 to 1994, Evans' own research and publications dealt with a wide array of materials phenomena, including, to name just a few, the processing and behavior of metal matrix composites, thin film systems, and fundamental and applied aspects of metal-ceramic interfaces. Evans published approximately 200 papers during this period, many co-authored with UCSB graduate students or colleagues drawn from universities and companies from across the world. Evans is the "senior" author on most of these publications, reflecting his roles as instigator of the research, contributor to all aspects of the effort, and someone who always provided his share, if not the lion's share, of the writing. Evans' reputation as an exceptional communicator took hold during this period. His lectures at technical meetings, delivered with a hint of a Welsh accent, often drew standing-room-only crowds, whether focused on a specialized topic or covering a broad range of subject matter.

The Evans family took advantage of the lifestyle the Santa Barbara area offers, including the wine country in the valley just over the Santa Ynez Mountains and the beaches and Pacific Ocean to the west. Their house had a large swimming pool, and daughter Jaye Evans reports that Tony and his wife, Trisha, spent many of their weekends reading poolside, with Tony periodically tossing his three daughters into the pool one after the other. For much of his career, Tony took a daily run. Colleagues visiting UCSB would typically gather at noon for a jog with Tony on the beach that rims the campus. His ability to focus his attention on his work has been emphasized. Jaye Evans reports that her father was equally adept at focusing his time on his family. As the author of this memoir had always suspected, Jaye verifies that Tony never brought work home, either in the evenings or on weekends. The family frequented the Santa Barbara restaurants, and Tony and Trisha enjoyed going to the movies, especially to see independently produced films. Tony had a green thumb, and most of his colleagues will be surprised to learn that it was he who was responsible for the plants and flowers always gracing the Evans' home. Tony's thumb was equally good at making household repairs. The Evans family also took advantage of many opportunities for travel, and there were memorable trips to the United Kingdom, Europe, and Africa. Here, again, Tony's management and organizational skills proved critical in seeing that his three young daughters and his wife, who was inclined to travel with an unusually large number of suitcases, caught their trains and planes on schedule.

Harvard, Princeton, and Completing the Circle Back to UCSB

It has been noted that Tony Evans had a hard time resisting a good problem. He also had a hard time resisting an attractive job opportunity, and it was in response to one such offer that Evans moved to Harvard University to become the Gordon McKay Professor of Materials Engineering in the Division of Engineering and Applied Sciences. One of the attractions of the Harvard position was that it involved teaching and research but no administrative expectations other than those attached to his own research activities. He stayed at Harvard from 1994 to 1998, and then accepted another attractive offer from Princeton University to assume the Gordon Wu Professorship in the Department of Mechanical and Aerospace Engineering. At Princeton, Evans had again hoped to avoid serious administrative responsivities, but his proven administrative talents were too tempting for the university, and he was persuaded to head the Princeton Materials Institute. As was the case during Evans' earlier tenure as departmental chair at UCSB, his research colleagues were largely unaware of his dual responsibilities.

Evans' unerring eye for good problems, combined with his collaborative spirit and scientific generosity, had the expected energizing effect on colleagues, graduate students, and postdocs at Harvard and Princeton.[20,21] He offered a popular course on the thermo-mechanical behavior of engineering materials for Harvard and Massachusetts Institute of Technology (MIT) graduate students, taught jointly with Subra Suresh, a professor at MIT. Formally the course alternated being offered at Harvard one year and then at MIT the next. An amusing anecdote concerning this arrangement is that MIT had no problem listing a Harvard professor in the MIT course catalog. But because there was no precedent for such a listing at Harvard, considerable wrangling transpired before an MIT professor could be listed in the Harvard catalog. During the eight years when Evans was on the East Coast, the Study Groups followed him, as did his research interactions with many colleagues throughout the United States and the larger world. One outcome of the research on metal foams carried out during this period was a highly cited book, *Metal Foams: A Design Guide*.[22] Another was the significant boost to the field of structural lattice materials, achieved through Evans' interactions with many colleagues, including Vikram S. Deshpande, Norman A. Fleck, and Haydn G. N. Wadley.[23]

The attraction of Santa Barbara and UCSB for Tony and Trisha remained strong, and they returned to UCSB in 2002, with Tony holding a joint appointment in the Departments of Materials and Mechanical Engineering and focusing primarily on teaching and research. As must be clear from the prior narrative, Evans was continually adding new areas to his plate of research interests but seldomly losing interest in former activities. Thus, back at UCSB, he continued to work broadly on problems dealing with the thermo-mechanical behavior of structural materials, including ongoing studies on CMCs and TBCs. Evans also initiated new major research activities when he returned to UCBS. These included research into the efficacy of all-metal sandwich plates for structural design against blasts, the development of new constitutive models for characterizing the deformation and failure of ceramic materials used to defeat ballistic penetration, advancing materials and structural design for the high temperatures associated with hypersonic flight, and a foray into biology with studies of the mechanical aspects of cellular adhesion.

The attack of September 11, 2001, on the World Trade Center in New York caused the U.S. Office of Naval Research and other research agencies around the world to initiate funding into enhancing the blast resistance of structures. A mode of funding for relatively large five-year multi-university research initiatives, MURIs for short, used by the U.S. military funding agencies had been launched more than a decade earlier. Evans had led the teams that prepared the successful proposals for MURI funding for the CMC and TBC projects. He again led a team, now drawn mainly from UCSB, Cambridge University, Harvard, and the University of Virginia (UVA), to successfully propose

MURI-funded research on metal sandwich plates designed for enhanced blast resistance. As a personal aside, the author of this memoir only once noticed Evans show any signs of work fatigue—which occurred towards the end of the preparation of this proposal. Proposal writing was another skill at which Evans excelled.

The concept of all-metal sandwich plates, including metal core structures, was new and required consideration of both structural geometry and manufacturing issues. Critically, the sandwich concept exploited fluid-structure interaction effects that occur under blast conditions, especially in a water environment, to achieve enhanced performance. As opposed to nearly all of Evans' earlier research, the intellectual center of gravity of the structural blast project lay much closer to structural engineering than to materials science. Evans' colleagues who had worked with him over the years could not help but be impressed at how easily he transitioned into this new project. Evans the engineer came out of the closet, and he again provided both leadership and research contributions to the project.[24] Laboratory-scale experiments simulating blast loadings, devised by Deshpande and Fleck, were carried out at Cambridge University. One ingenious series of experiments employed slugs of sand, calibrated to mimic a blast and shot from a laboratory "gun," to impact the sandwich plates. Full-scale blast tests of specially designed and manufactured metal sandwich plates for ship hulls were carried out by the U.S. Navy, with Wadley at UVA serving as the primary contact between the MURI researchers and the Navy. Study Groups for the structural blast project were held at either UVA or Cambridge University, usually in the spring or summer months.

While Evans was chair of the Materials Department at UCSB, he was involved in all departmental hiring, but he was also central to identifying and attracting faculty in the general area of engineering materials even when he was not the chair. Evans was involved in recruiting Clarke, Levi, McMeeking, Suo and Zok during his first period at UCSB, and he helped recruit a younger generation of colleagues during the second period, including Deshpande and Matthew R. Begley. Although Deshpande would return to Cambridge University after only two years at UCSB, he and Evans had unusually productive collaborations. In work that had begun prior to Deshpande's arrival at UCSB, they created a new constitutive model characterizing the deformation, damage, and failure of high strength ceramics.[25] With its inclusion in the large computational codes used to simulate ballistic penetration of ceramic armor, this model significantly advanced the predictive capabilities of the codes. Deshpande and Evans also produced a series of papers on fundamental aspects of the mechanics of how living cells interact with their external environment. Evans had done earlier work on the microstructure of natural composite materials such as nacre, elucidating how a composite that is made up almost entirely of a very brittle component can have high strength and toughness.[26] The work on cells was the first effort on living systems for the two researchers, however. They carried out experiments and developed models to measure and describe the forces that cells exert when they adhere to soft material substrates and are subject to various stimulations.[27]

Evans' untimely death occurred at the age of 67 in the prime of his life. He learned he had colon cancer about six months prior to his death on September 9, 2009, and during this period he and his doctors strove valiantly to return him to good health. Despite his health problems, Evans co-authored fifteen papers in 2009, and more than twenty papers listed him as a co-author in the two years that followed. The topics of his papers published in 2009 underline the breadth of his scientific interests: heat pipes and materials for hypersonic flight, unresolved issues in plasticity for applications at small scales, fluid-structure interaction in the design of corrugated core sandwich plates, toughness of brazed joints, thermal expansion properties of lattice materials, forces exerted by cells on rough substates, TBC delamination under high thermal flux, and ballistic penetration by ceramic spheres. A special issue of the *Journal of the American Ceramics Society* (2011) was published two years after Evans' death, collecting papers presented at a meeting in his honor held at UCSB.

The many honors and awards received by Tony Evans are listed at the end of this memoir. He received essentially all the relevant honors that could be bestowed by the American Ceramic Society. The breadth of Evans' scientific and technological reach outlined in this memoir is reflected by his election into the National Academy of Engineering and the National Academy of Sciences in the United States and the Royal Academy of Engineering and the Royal Society of London in the United Kingdom. In 2008, Evans was made a Fellow of Imperial College, his alma mater, a recognition he greatly appreciated. Tony's wife, Trisha, passed away in Santa Barbara in 2019. He is survived by his daughters, Samantha, Pollyanna and Jemina (Jaye), and his grandchildren.

Two additional photographs of Tony Evans are reproduced in Figure 2. The one on the left is Jaye Evans' favorite picture of her father, while the one on the right shows Tony, uncharacteristically, in suit and tie. Evans' students, colleagues and collaborators will agree that these pictures, along with the one at the beginning of this memoir, indeed capture the person who brought us together and brought out the best in us.

Figure 2. Tony Evans in everyday attire.

Figure 3. Tony Evans expounding at a meeting in more formal attire.

Honors and Awards

1967	Matthey Prize (Imperial College)
1974	Ross Coffin Purdy Award (American Ceramic Society)
1979	Richard M. Fulrath Award (American Ceramic Society)
1980	Robert Sosman Award (American Ceramic Society)
1983	Van Horne Distinguished Lecturer (Case Western Reserve University)
1984	Clyde Distinguished Professor (University of Utah)
1986	Hobart N. Kraner Award (American Ceramic Society)
1988	John Jeppson Medal (American Ceramic Society)
1988	Orton Lecture (American Ceramic Society)
1993	Honorary Fellow (International Congress on Fracture)
1994	Griffith Medal and Prize (The Institute of Materials)

1997 Member National Academy of Engineering (US)

1998 Peterson Award (Society for Experimental Mechanics)

2000 Distinguished Life Member (American Ceramic Society)

2000 Fellow Academy of Arts and Sciences (US)

2000 Turnbull Award (Materials Research Society)

2001 Mellor Memorial Lecturer (The Institute of Materials)

2003 Nadai Medal (American Society of Mechanical Engineers)

2001 Fellow, Royal Society of London

2002 Humboldt Research Award for Senior U.S. Scientists (Germany)

2005 Gold Medal (ASM International)

2005 Member National Academy of Sciences (US)

2006 Fellow Royal Academy of Engineering (UK)

2008 Fellow of Imperial College

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This memoir is informed by Tony Evans' published papers, recollections of his colleagues and collaborators, especially Carlos Levi and Robert McMeeking, as well as the author's own close collaboration with Evans from the late 1970s until Evans' death thirty years later. The author has also been fortunate to have had exchanges with Evans' youngest daughter, Jamine (Jaye) Evans, who supplied family information along with Figures 2 and 3. Specific mention should also be made of the following published commentaries on Evans' life and contributions: a testimony celebrating his 65th birthday in the *International Journal of Materials Research*,[28] an obituary in the November 29, 2009, issue of the *Guardian* newspaper,[29] a tribute in a special issue dedicated to Evans of the *Journal of the American Ceramic Society*,[30] and a memoir for the U. S. National Academy of Engineering.[31] Of necessity, this memoir has cited the names of only a small fraction of the hundreds of researchers who have worked and published with Evans. The author apologizes for omitting specific mention of many of Evans' students, colleagues and collaborators who were central to his life and technical contributions.

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