A HISTORY OF THE FRACTOGRAPHY OF GLASSES AND CERAMICS

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ABSTRACT

The science of fractography of brittle materials evolved from failure analysis problems involving brittle materials such as cast iron and early steels. Early analyses focused on general patterns of fracture and how they correlated to the loading conditions. Scientific and engineering explanations gradually were developed for the observed patterns. Advances in microscopy and flaw-based theories of strength and fracture mechanics led to dramatic advances in the state of the art. The Griffith theory of flaw-controlled strength gradually became accepted, especially when the microscopic flaws themselves were finally detected by Ehrnberger. Improvements in processing control in the 1970s led to stronger ceramics that were more amenable to fractographic analysis and even fracture origin determination. This history is a story of the people who were pioneers in the field, of theoretical developments on the strength of brittle materials, of advances in materials science including the fabrication of stronger materials, of developments in microscopy, of the publication of key books, and of standardization.

INTRODUCTION

Some deem fractography as the study of fracture surfaces, but I take a broader view. Fractography is the means and methods for characterizing fractured specimens or components. A simple examination of the fragments and how they fit together to study the overall fracture pattern is a genuine fractographic analysis, even if the fracture surfaces are not examined.

When I wrote my fractography guide book between 2003 and 2007, my curiosity was aroused about how the field had evolved. Articles existed about how the fractographic analysis of metals evolved, but there was no analogue for ceramics and glasses. I first wrote about this topic in 2008 for the Stanza Lesna conference on Fractography of Advanced Ceramics. At the time, I was unable to include any illustrations of photographs of key fracture features, or photographs of our forebears. I therefore have written this more comprehensive illustrated article to remedy these shortcomings and to expand some key points, particularly on the work of Mr. Roy Rice and standardization activities.

The key scientists, engineers, and analysts who contributed to our field are shown in Figure 1. This figure is a slightly revised version of my figure in the 2008 paper. In the text below, I have used underlined italics to highlight the first documented instances of new terms such as: "hackle," "mirror," and "Walther lines."

EARLY STUDIES

Derek Hull credits Robert Hooke with the first reported observation of a fracture surface, of any subject made using a microscope (Figure 2). Hull also gave a brief history of the use of fractography for minerals, metals, and lithic structures over the centuries.
Figure 1. Chronology of the Evolution of the Science of Fractography of Brittle Materials
Figure 2. Illustration by Robert Hooke of the fracture surface of Keton limestone, a shapeable stone with an interesting microstructure. It is formed by precipitation of calcite and is used for architectural projects. From Micrographia, 1665, (Ref. 7). The bonded spherical nodules are about 0.5 mm diameter according to Hull. (Courtesy Project Gutenberg eBook.)

Although he showed no pictures, Brodmann in 1894 made some of the earliest observations of overall fracture patterns and fracture surfaces of glass rods tested in tension, bending, and torsion. His paper "A few observations on the strength of glass articles" was published in Reports of the Scientific Society of Gottingen. Most of the paper was about the testing procedure and the strength results. His excellent fractographic observations were in a single paragraph at the end of the paper. Brodmann used the word *mirrors* to describe the smooth area around an origin and noted that:

"In general, the radially measured size of these mirrors was larger, the smaller was the strength."

This was a very important observation, which eventually was quantified. Fracture mirror size analysis today is an important fracture analysis tool.

Charles De Freminville (1856 to 1936) wrote the first comprehensive treatment of the subject. He was identified as a mechanical and industrial engineer in Paris, working as a consultant for Schneider works in 1919. He was concerned with brittle fractures in brittle steels and iron in which negligible deformation occurred. He observed that the fractures bore a good resemblance to those in glasses and bitumens. It seemed that some such fractures were so sudden and violent that they could be deemed "explosive." He wrote two long papers in *Revue de Metallurgie* in 1907 and 1914. The first was fifty-one pages in length and was titled the "Character of Vibrations Accompanying Impact, Observations from the Examinations of Broken Pieces." Impact testing was proposed as one way of measuring the linear resistance of brittle metals, a suggestion that was realized years later with the adoption of Charpy impact testing. Overall there are thirty-eight figures in the first paper, many with multiple parts, which show a variety of classical fracture patterns. The second paper was a major expansion and almost book length (eighty-five pages). Each paper included superb combinations of schematics and photographs of both the overall breakage patterns and fracture surfaces. For example, Figure 3 shows several of his illustrations for bending fractures in a round axle as well as glass rods for comparison. This extraordinary sketch shows glass rod fracture patterns with multiple bending fractures. He wrote that once elastic waves reverberate, regions initially in tension could be exposed to transient compression stresses and vice versa. One whole section of his paper covers secondary fractures caused by reverberations of elastic waves once the primary fracture had occurred.
Figure 3. Illustrations by De Freminville in 1907. The top shows fracture in a brittle cast iron axle, and the lower figures show bending fractures in glass rods. (Reprinted with permission of EDP Sciences.)

Figures 4 and 5 show fracture types that are quite recognizable to the modern fractographer. De Freminville categorized fractures as “direct” or “indirect.” “Indirect fractures,” shown in Figure 4b were bending fractures by overloading or impact on the opposite side of the fracture origin. De Freminville observed that the fracture occurred opposite the struck surface and the crack propagated up
Figure 4. Illustrations by De Freminville in 1907 and 1914. (a) shows a glass plate. (b) shows a fracture surface of a beam broken in bending. De Freminville deemed this an "indirect fracture" since the initiation of fracture (as shown by the fracture mirror schematic on the bottom) occurred opposite to the impact site shown by the top arrow. (Reprinted with permission of EDP Sciences.)

Figure 5. "Direct fractures" are those that occurred at an impact site, according to De Freminville. The two images on the left show sharp-contact-initiated fractures in a block of glass, and the two on the right show blunt contactor ("Hertzian") cone cracks. (Reprinted with permission of EDP Sciences.)

and joined with the impact site. "Direct fractures" were those where the origin was initiated at the impact site (Figure 5). Several illustrations such as Figure 5 illustrate classical Hertzian cone cracks in flat plates or in glass spheres dropped from a height. His carefully drawn breakage patterns reveal classic bending stress branching patterns in both square plates and long slabs. His paper included stress distributions from other sources that were relevant to the fracture. Little was said about the fracture origins themselves. De Freminville used the French word "le foyer" which may be translated as the "source." For the case of "direct fractures," the impact site itself was assumed to have been the origin.
Figure 6. Fracture surface of a strong broken glass rod. The fracture mirror and even the initiating flaw are readily observable. De Freminville did not use the term "mirror," however, as Brodmann had before him. De Freminville also did not comment on the character of the flaw. (Reprinted with permission of EDP Sciences.)

Nevertheless, surface contact or abrasion damage flaws are in fact easily seen in several of De Freminville's figures, such as Figure 6. It is astonishing that his 1907 perceptive paper showed
Figure 7. De Freminville observed rib-like undulations in the fracture surface. (Reprinted with permission of EDP Sciences.)

Figure 8. De Freminville commented on lines that later became known as "hackle lines." In this illustration, he showed how overlapping crack segments create such lines. (Reprinted with permission of EDP Sciences.)

numerous examples of what later became known as "Wallner lines," the telltale gentle arc-shaped lines ("ribs") on fracture surfaces, as shown in Figure 7. He correctly interpreted these lines as undulations in the fracture surface as the crack radiated outwards from a fracture origin. The telltale lines created by an impact are concentric about the impact site and lead one's attention back to the origin. Hackle lines are also shown or depicted in the illustrations, such as Figure 8, although he described them as striae. He compared rib lines and hackle lines in glass and sandstone.

De Freminville set an example for all future fractographers by often showing matched drawings and photos such as Figure 8. He also showed reconstructed parts and illustrations of the fracture surfaces. A section of the 1914 paper also shows fascinating illustrations of broken diametrically-loaded 30 mm diameter glass balls, as shown in Figure 9.
Figure 9. Fracture patterns in diametrically compressed glass balls. The top row shows side views where the fracture origins ("c") are on the outer rim at the equator. The figure on the right shows the fracture pattern from an interior origin site. The second row shows top views of the same pieces. The final figure on the bottom illustrates the stress distribution. (Reprinted with permission of EDP Sciences.)

Figure 10. Fracture of a glass mirror caused by center heating. The tensile stresses at the origin site F on the cooler rim were moderate to large since branching occurred. The waviness of the cracks once they propagated further into the warmer, compression-stressed portion of the plate, is a telltale characteristic of thermal stress fracture. (Reprinted with permission of EDP Sciences.)
One of his final illustrations in the 1914 paper, Figure 10, is a charming illustration of a glass mirror fracture due to center heating from an oil lamp placed too close to the mirror. Uneven heating creates tensile stresses on the cooler rim. Edge-initiated fractures in glass are a problem to this day.

De Freminne's 1914 paper was a major expansion of the first and included additional loading conditions such as thermal stresses. It is curious that the journal publishers allowed the repetition of so many illustrations in their journal only a few years later, but they are to be commended since the second paper can be used as a standalone document. Many of the figures are enlarged in the second paper. One addition was an explicit section on component reconstruction. Many more fracture examples were shown including some for brittle metals such as broken railroad tracks and wheel axles. Radiating hackle lines were termed strike. Some illustrations and schematics showed overlapping crack portions that formed hackle lines (lanes). He described what we now call fracture mirrors although he did not use that term as Brodmann had done earlier. The smooth central region that was the focus of all the splintering lines seemed to surround an origin site. The smooth central region was also surrounded by a dull surface portion that he correctly attributed to surface roughening. He also ventured a discussion of the flaws located at the center of the mirror in cases of slab bending and impact bending fractures. Keeping in mind the photographic and microscopic limitations of the day, the flaws he showed were large surface contact damage, handling, or grinding flaws. He astutely observed that brittle materials are susceptible to surface flaws, but showed some examples of internal origins in brittle metallic tension specimens. In December 1919, De Freminne was invited to give a lecture at the Annual Meeting of the American Society of Mechanical Engineers. A sixteen-page summary article of his fractographic work on the topic of the reliability of materials and the mechanisms of fracture was published in English after the meeting. De Freminne's three papers constitute the first significant treatment of the fractography of brittle materials. A web search of his name indicates that he was a leader in the "scientific management" movement of the early 1900s, and was active in the American Society of Mechanical Engineers and used modern management techniques applied to auto manufacture. He lived from 1856 to 1936. I have not been able to locate a photograph of him.

PROGRESS IN THE 1920s – 1950s

Only a short time later in 1920, Alan Griffith (Figure 11) published his seminal paper that identified flaws as the nuclei of fracture. There is no indication that he was aware of De Freminne's papers. Fine filaments of pristine drawn glass had tensile strengths approaching the theoretical strength, but strengths decreased with time and/or exposure to surface damage sources. He showed that the strength of a uniformly stressed plate containing an elliptical through-crack of size 2c in a uniform tensile stressed plate in plane stress is:

\[ \sigma_c = \sqrt{\frac{2E\gamma}{\pi c}} \]  

where \( \sigma_c \) is the fracture stress, \( E \) is the elastic modulus, and \( \gamma \) is the fracture surface energy to create unit surface area. (Incidentally, the first paper had an extra Poisson's ratio in the denominator, that was corrected in his second paper without explanation.) The critical feature of this relationship is that strength is inversely proportional to the square root of flaw size. The larger the flaw, the weaker is the structure. Griffith stated, "the general conclusion may be drawn that the weakness of isotropic solids ... is due to the presence of discontinuities, or flaws, as they may be more correctly called, whose ruling dimensions are large compared with molecular distances."
A History of the Fractography of Glasses and Ceramics

Figure 11. Alan A. Griffith (1893 – 1963).

Notwithstanding some confusion as to whether the surface energy was simply the thermodynamic surface energy or a larger effective fracture surface energy, researchers now had some guidance as to the size of the flaws they should look for with their microscopes. Griffith showed only one sketch of a hypothetical crack and no photomicrographs, but he estimated the crack size had to be 1.5 µm (Ref. 13) or 5 µm (Ref. 12) for his conventional tension strength tests. Griffith believed that flaws were molecular fault regions in glass that would act as fracture nuclei. The quest to find minute Griffith flaws took many years and was not completely settled until the advent of electron microscopy.

De Freminville had already shown some relatively large strength-limiting flaws in glass in his photos and sketches (see Figure 6 of this paper.) The concept of Griffith flaws applies equally well to large, visibly observable flaws and to submicroscopic flaws in very high strength materials. Griffith's paper was not immediately accepted by many in the field. (For more on this see the fine review of the history of glass strength studies by Holloway.14) For many years researchers strove to find the submicroscopic flaws they could not see and argued over their true nature and whether they really existed. The expression “Griffith flaw” was typically used to describe submicroscopic sized flaws they could not readily detect. An outstanding biography on Griffith's life and his work15 analyzes some of the minor mistakes in his equations, but these do not detract from the significance of the work.

Significant advances in understanding strength and flaws in glass were made by Frank Preston over a long and productive career (Figure 12). Born in Leicester, England, he began writing about his glass work in 1921 when he studied the flaws created in glass surfaces by grinding and polishing, contact with balls, and scoring with glazer's wheels.16 Figure 13 shows some of his illustrations. He used the terms median and lateral to describe cracks created under a glazer's diamond, as shown in Figure 14, a nomenclature that has persisted to this day. He noted that:

"It is clear from these observations that ... there are deep flaws extending far below the surface irregularities..."

This was one of the first observations that cracks can penetrate far deeper than the grinding surface roughness damage. It was recognized as “a rather startling conclusion” that was verified by additional work by a reviewer in the discussion section at the end of the paper. Another commenter said that:

"The present paper constituted a marked advance in the subject. Apart from its scientific value, it should be of great assistance to manufacturers."

10 · Fractography of Glasses and Ceramics VI
A History of the Fractography of Glasses and Ceramics

Figure 12. Frank Preston (1896 – 1989). (Courtesy of the American Glass Research Company.)

(a)  
(b)  

Figure 13. Preston’s photos of damage caused by a hard ball,\textsuperscript{13} (a) shows the top surface with ball motion from left to right (arrow). (b) shows a cross sectional view of the damage underneath as seen on the fracture surface. The top half is a mirror image of the actual fracture surface on the bottom. (Reprinted with permission of IOP publishing.)

Years later, Preston’s colleagues published a paper\textsuperscript{17} that showed how soft metals could damage glass surfaces by creating chatter sleeks that were a series of shallow partial cone cracks.

Preston emigrated to the United States in 1921 and soon founded Preston Laboratory in Butler, Pennsylvania. In 1926 Preston wrote the first of a series of percussive papers on the strength of glass\textsuperscript{14} in which he acknowledges Griffith’s notion that flaws control strength. Preston discussed blunt contact cracks, stones from manufacture, and fractures produced by heating and cooling. It is curious that Preston, like De Frémionville before him, referred to some virulent fractures (e.g., thermal shock) as “explosive.” Figure 15 shows what we now refer to as a fracture mirror. Preston describes some of the fracture markings surrounding an “explosion center.” Referring to the figure, he described X as a:

“tiny semi-circular area of bright (“polished”) fracture, surrounded by a dull fracture P, and it is succeeded by a coarser structure Q, . . . which may be recognized as hackly fracture with the unaided eye.”

We now refer to these as the “mirror,” “mist,” and “hackle” regions.
Figure 14. Preston's photos of damage caused by a glazer's diamond. (a) is an end-on view where “O” shows the axis of scoring (in and out of the page). The original glass surface is A-A. B-B shows "lateral" cracks and C is the "median" crack. (b) shows the fracture surface of a scored plate broken in bending where the crack ran from left to right. The shallow scoring median cracks are visible at the top as well as the many curved Wallner lines typical of a bending fracture. (Reprinted with permission of IOP publishing.)

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**Diagram of an explosion centre and distribution of hackle-texture.**

Figure 15. Preston's schematic of a fracture mirror (Reference 18). (Reprinted with permission of the Society of Glass Technology.)

Preston in 1926 said that the "explosion center no doubt represents the site of some pre-existing minute 'flaw'" and "the fracture originates in a minute spot of possibly ultra-microscopic size, and spreads quietly over a tiny area-the semicircular spot." It is curious that he seemed reluctant to use the word "flaw" as Griffith had done earlier. Preston always showed the word in quotation marks.

Further into the paper, Preston described the arced or ribbed shape lines that we now call "Wallner lines." He called them "tide marks" or ripple marks, and he correctly deduced that they were formed by an oscillating stress system. He also correctly observed that for violent fractures the oscillations that produced the rib lines did not reach the crack front simultaneously, but at different times causing the curved arcs (Figure 16). This perceptive observation anticipates Wallner's analysis in 1939 and, had Preston been more mathematically inclined, the rib lines today may have been called "Preston Lines." The paper further discussed the effect of stress upon crack branching or forking. He even said:

"hackle is incipient forking (page 257), the first stage in the development of a radiant crack."
Figure 16. Preston's schematics of the fracture surfaces of glass plates.\textsuperscript{18} (a) shows a thick rolled plate which was not annealed, as was customary. The severe internal residual stresses cause a fracture surface similar to that of tempered glass. If is for "hackle" lines in a herringbone pattern. "C" denotes what we now refer to as Wallner lines, illustrating that the crack led in the interior due to stress gradients. (b) shows the fracture surface with no hackle and only curved Wallner lines in a location of the same plate with tensile stress of lower magnitude. (Reprinted with permission of the Society of Glass Technology.)

Preston felt that, once a hackle fissure parallel to the main crack surface grew broad enough such that it extended through the thickness of a plate, the crack would fork. Preston concluded that the object of his paper was to "correlate various fractures in glass and other brittle materials,... in a general system based on their genesis and on the stresses initiating and extending them." Most of his optical micrograph figures had magnifications of 44 to 120 power.

Preston's 1926 paper elicited a number of comments that were published as a group in the Journal of Glass Technology in 1927.\textsuperscript{19} Preston replied with further comments on "flaws." In a brilliant anticipation of Weibull's 1939 analysis, he said:\textsuperscript{19}

"A glass may contain a virtually infinite number of nuclei (flaws), but rupture will not start in the absence of stress. On the other hand, glass would never break under the stresses to which it is commonly subjected if it had no nuclei. The particular condition that a nucleus should be present in, or very close to a particular point (the point where the tension is greatest) can only be expressed as a probability function. If the test is made on such a fashion that the tension is absolutely uniform over a large region, the probability that a nucleus will be located in the critical region amounts to certainty, .... If on the other hand, very small specimens are used, or the stress is very uneven so that only a small region experiences the maximum tension, then the probability of a nucleus being in the critical region is by no means a certainty, and the stress throughout the mass may have to be raised much higher until a great enough tension is produced somewhere else where there is a nucleus."

"Under these conditions, a larger series of tests will show a high probable error (variability) for the individual measurements, and when we have tested ten thousand pieces, we shall still not be able to predict the strength of the next piece with any accuracy."
Preston continued to publish regularly with as many as 200 papers on glass and a like number on ornithology, geology, ecology, and even politics! One fascinating, but very short paper in 1935 showed a relationship between the branching angle and the stress state\textsuperscript{20} as shown in Figure 17. For example, uniaxial stresses, such as in a tension or flexural strength test, cause 45 degree branches. Equibiaxial stresses, such as a ring-on-ring disk strength test, have 180 degree angles. Seventy six years later his trend curve of branching angle versus biaxial stress ratio needs further analytical and

Figure 17. Preston's 1935 paper\textsuperscript{20} showed that the angle of forking (branching) varied with stress state. His Fig. 1 is for uniaxial tension; 2 is for equibiaxial tension; 3 is torsion. The abscissa of his Figure 4 is the ratio of the two principal stresses.

Figure 18. Figures from Preston's 1939 bottle-breakage paper.\textsuperscript{21}
experimental verification, especially for ceramics. Practical problem solving led Preston to write papers in 1939\textsuperscript{21} and 1942\textsuperscript{22} on bottle breakages (Figure 18). In the former, he said that the principles of fractographic analysis and pattern analysis:

"... are often useful in determining whether a bottle was broken the way a complainant in a lawsuit says it was or whether the case contains elements of deceit."

Preston’s 1939 bottle-breakage paper\textsuperscript{21} and a second 1942 paper\textsuperscript{23} on mechanical properties of glass treat the topic of static fatigue, or the time-dependent degradation of strength while under load. The later 1942 paper includes much colorful language and is entertaining to read:

"A lecture on the mechanical properties of glass a few years ago might have been regarded ... on a par with the metaphysical significance of elephants or the moral significance of liquid air, or that mechanical properties of glass could be described in exactly the same word as the famous treatise on the snakes in Ireland, viz. "There are none."

Later he wrote:

"No one will deny, however, that the behavior of cast iron is angelic, in respect to brittleness, as compared with the behavior of glass."

He also wrote simple declarative sentences:

"Under ordinary circumstances, glass breaks only in tension and the fracture is at right angles to the maximum tension." "The ‘strength of glass’ is a very elusive quantity."

The first sentence is evidently the first formal statement of what we now refer to as the law of normal crack propagation, which is: \textsuperscript{3} "A crack propagates normal to the direction of local principal tension stress." It is very odd, but De Fremerville, who was right in so many of his observations in his 1907 paper,\textsuperscript{5} seemed to have gotten this wrong (on his page 878):

"Une Tension normale au plan de la cassure n’est pas favorable à la propagation par fissilité. Elle ne peut produire qu’un arrangement."

which may be translated to:

"A tension normal to the fracture plane is not favorable to the propagation of the crack. This tension can only create a pull out (tear)."

In the conclusions in his 1942 Journal of Applied Physics paper,\textsuperscript{24} Preston summarized the art of fractographic analysis:

"From the beginning of time to its end, no two cracked surfaces will fit each other, unless originally they were part of the same piece. Cracks are as distinctive as fingerprints. ... Now the important thing about cracks is that they must be propagated. They do not originate all over the final fracture surface, but at one tiny spot, and from thence are propagated out to the rest of the area. This fact and the fact that the telltale marks or “fingerprints” of the process are left on the surface, provide the groundwork for the subject of Fracture Diagnosis, which in the last decade has become an important minor branch of physical science.”
I have been asked many times over the years by forensic investigators whether fractures are as distinctive as fingerprints, and I have directed the inquirer to the quote above. Summaries of Preston’s contributions and career have been published and a web page about him is maintained by the American Glass Research Company, the modern day descendant of Preston Labs.

In the meantime, considerable progress was being made in Europe in Professor Adolph Smekal’s (Fig. 19) Institute of Theoretical Physics in the University of Halle in Germany between 1935 and 1945. Smekal was an Austrian who had a long-term interest in the practical aspects of brittle materials fracture in addition to his work on quantum physics. He published on glass fracture between 1935 and 1959. He broadened the molecular physics theory of crack initiation and propagation beyond Griffith’s approach. Some consider him an early pioneer of what would later become fracture mechanics theory. Smekal focused on the arcs, ripples, fracture mirrors, and lances (hackle). Some of his figures are shown in Figures 20 and 21. He correctly deduced that the size of the fracture mirror was inversely related to the stress in the body at fracture, but unfortunately he used the mirror’s area for the size and not its radius. He also analyzed the stress data in terms of the load divided by the remnant area outside the mirror region. Smekal came close to the fundamental relationship between stress and mirror size, and he even had tables of mirror constants for different materials, but he did not quite have it right. His later publications with images of crisscrossing Wallner lines are exquisite. He showed how crack velocities could be computed inside fracture mirrors and how terminal velocity was reached while the crack was still forming the smooth mirror. He used the term “mirror” (“der Spiegel”) in these early publications as Brodmann had done in 1894. He also began to show similarities and differences between fracture markings in glass and Plexiglass. The authors of two biographical sketches of Smekal lamented the fact that, since most of his work was published only in the German language, Smekal may not have been given the full credit that he deserved for his work. The journal Glastechnische Berichte had a single page obituary for Smekal in 1959. A new biographical article on the 50th anniversary of Smekal’s death lists his accomplishments.

Figure 19. Adolph Smekal (1895 – 1959) (a) from the 1930s (American Institute of Physics, College Park, MD), (b) from his obituary in 1959, Reference 36. (Reprinted with permission of the German Society of Glass Technology.)

16 · Fractography of Glasses and Ceramics VI
Figure 20. Fracture surface of fire-polished glass rods. (a) shows an internal origin and mirror, and (b) shows a surface origin and mirror. (Reference 30). (Reprinted with permission of the Society of Glass Technology.)

Figure 21. Schematic of a glass rod with a surface original break. As described by Smekal in 1936, K is the flaw at which fracture starts, S is the mirror, R the region of increasing roughness, and F is an inclined grooved surface. (Reference 30). (Reprinted with permission of the Society of Glass Technology.)

Despite all of Smekal’s work and publications, it was a single short nine page paper by a visiting postdoctoral worker, also an Austrian, that was to have the greatest impact. Dr. Helmut Wallner, shown in Figure 22, had done his doctoral work on physics and mathematics at the University of Vienna, but then went to Smekal’s institute in 1938. His now famous paper: “Linienstrukturen an Bruchflächen” (Linear Structures on Fracture Surfaces) was published in the fateful month of September 1939. This paper definitively and mathematically explained the cause and shapes of the curved ripple lines on glass fracture surfaces that had been commented on for decades by previous authors. The ripples were indeed caused by elastic waves interacting with the crack front as it propagated. Wallner even showed how the crack velocity could be analyzed from the arced lines. This was only one of two papers that Wallner ever wrote. He left the technical field shortly afterwards. Over the succeeding years, the terminology in the field changed, and what had been known as “rib lines” or “ripples” became “Wallner lines.”
Figure 22. Helmut Wallner (1910–1984). (Courtesy of H. Richter.)

Figure 23. Wallner's figure 2 (left) of a fracture surface of a glass rod broken in four-point flexure. His figure on the right illustrated how a crack radiated outward (thin concentric semicircular lines) from an origin site B. Elastic waves generated at a surface irregularity S interacted with the advancing crack front. (Reprinted with permission of Springer Science and Business Media.)

Smekal gave full credit to Wallner's work and Smekal even differentiated between various classes of Wallner lines (e.g., secondary Wallner lines in Fig. 5, ref. 33, 1950). A new biography of Helmut Wallner was prepared by Dr. Herbert Richter in 2008.

Beginning in Berlin in 1937 and continuing in Freiburg in the 1950s, Schardin (Figure 24), Struth, and colleagues conducted experiments using very high speed spark-camera photography to measure the terminal velocities of cracks in glass that were struck by bullets. Time lapse photography with extremely small time intervals enabled them to monitor individual crack extensions.
Figure 24. Professor Dr. Ing. Hubert Schardin (1902 – 1965). (Wikipedia)

Figure 25. Schardin's time-lapse figure showing crack propagation from impact of a glass plate using a 24-spark camera at 300,000 frames per second. (From Reference 44 in 1955.)
as well as crack network expansions and damage-wave progressions with time (Figure 25). Terminal velocity varied from as low as 750 m/s for a flint glass, to 1500 m/s for soda-lime silica, to 2200 m/s for fused silica. These velocities were later confirmed by Barstow and Edgerton with their own electric-spark camera system in 1939. The terminal velocities were also confirmed by independent Wallner line analyses and some of Smeckat’s own results. Scharlin came to the realization that the terminal velocity of glasses was about 0.5 to 0.6 times the Rayleigh surface elastic wave speed. Figure 26 is another example of his work, showing crack propagation in a four-point loaded bend bar. Scharlin continued his work until 1962. His physics group at the University of Freiburg later evolved into the famous Institute for Material Mechanics. Reference 46 is a short obituary for Scharlin.

![Image of crack propagation](image)

Figure 26. A high-speed photograph of cracks propagating in a glass beam loaded in four-point bending. Two ultrasonic transducers are attached to the bottom of the beam created pulsed waves that marked the fracture surface. This example of Scharlin’s work is from Kerkhof’s 1974 book, Ref. 103. (Reprinted with permission of the German Society of Glass Technology).

Much later in the 1960s and 1970s, Field and colleagues at the Cavendish Laboratory of the University of Cambridge were able to confirm these terminal velocity speeds in glass using spark photography, ultrasonic fractography, and Wallner line analysis. They extended the work to ceramics such as magnesium oxide, diamond, sapphire, and even lithium fluoride.

J. B. Murgatroyd, who worked for two glass companies in England, wrote about fracture surface markings in glass in 1942. He correctly observed that overlapping parallel crack segments formed hackle lines where steps between the overlapping segments linked. He showed curved rib lines. Some of these were sharp “arrest lines,” where a crack stopped and then resumed propagation on a different plane. On the other hand, many of the rib lines he showed were Wallner lines that were more gentle ripples on the fracture surface. Murgatroyd evidently was unaware of Wallner’s 1939 paper, which may not be too surprising considering the events then taking place in Europe.

ADVANCES IN MICROSCOPY

At this point, it is appropriate to point out that nearly all examinations of fracture surfaces up to this time had been done with optical microscopes. The magnifications, the resolution limits, and the depth-of-field limits put constraints on what could be discerned and photographed. Interference microscopy enabled features smaller than the wavelength of light to be discerned, but only on very flat
smooth surfaces. Hull credits Tolansky and his group for leading work on this topic from 1943 for the next twenty years. Most fracture surfaces are neither flat nor smooth. The advent of transmission electron microscopy (TEM) using replicas in the 1930s broke through the limitations of optical microscopy. In 1943, Götz showed spectacular images of mist and hackle around fracture mirrors in glass rods as shown in Figure 27. Foncelet showed comparable images in 1958 and Peter in 1968. The most systematic work was done by Beauchamp, who in 1971 studied various regions in the mirror. His photos, some of which are shown in Figure 28, demonstrated that the formation of the mirror is a gradual progression of very localized crack-pain deviations from the main plane. Hackle forms when small perturbations and micro branching of the crack plane create tiny “tongues” of overlapping segments on the fracture surface. Atomic force microscopy in the 1990s has not changed these conclusions.

Figure 27. Götz’s 1939 photos of a glass fracture mirror. (a) is an optical image, originally at 26X. (b) shows two TEM images originally at 2500X from the mist-hackle zone with the crack running from top left to lower right. (Reprinted with permission of Springer Science and Business Media.)

Figure 28. Beauchamp’s TEM images from inside the fracture mirror in glass. (a) is one-third of the distance from the origin to the mist, and (b) is near the mist. The direction of crack propagation is from left to right. (Courtesy of E. Beauchamp.)
The advent of the scanning electron microscope in the mid 1960s revolutionized fracture surface examination due to the vastly improved depth of field, high magnification, and chemical analysis capability via energy dispersive spectroscopy. The heretofore elusive minute Griffith flaws could now be found and characterized, provided the examiner knew where to look! In addition, crack interactions with microstructure could now be studied more methodically.

WEIBULL THEORY AND FRACTURE MECHANICS

While the fractographers were documenting their findings, there were some important developments in materials science and mechanics. In 1939 Waloddi Weibull presented his new distribution function to account for the variability in strength of ceramic bodies. Strength depended on the size of the body. He did not show a single flaw or even a schematic of a crack in his papers, but it is clear from his descriptions that he envisioned an isotropic body as having a distribution of cracks that controlled strength. One of his data examples was for the strength of porcelain rods. He used an arbitrary, but shrewd, function for the risk of rupture for volume elements in the body, without concerning himself about the size of the flaws or what stresses would be necessary to propagate the crack. While he did not cite Griffith’s work, and modern fracture mechanics was still twenty years in the future, Weibull’s work led to a dramatic improvement in our understanding of the strength of brittle materials. Fracture occurs from the origin location that has the worst combination of tension stress and flaw severity.

An important analytical paper was written in 1951 by Ellen Yoffe on the “Moving Griffith Crack.” The stress distribution around a moving crack was analyzed and compared to that around a static or slowly moving crack. It was shown that at high velocities (0.6 of the shear wave velocity), the peak stresses moved out of the plane of the crack. This explained why cracks began to wobble or even bifurcate locally once they moved at high velocity. These local small bifurcations account for the mist and huckel regions around a fracture mirror.

Starting in 1953 the phenomena of multiple breakages also was accounted for by analyses of elastic-wave propagation during fracture. Miklowicz and later Phillips showed that unloading waves can reverberate and superimpose, and the phases of the waves (tension – compression) can switch after reflections. Kolsky analyzed the matter further and said that the stress field in the section being broken is extremely uneven and that a complicated local wave pattern is set up near the fracture plane with longitudinal and flexural waves being generated. Kolsky showed that, for rods tested in flexure, the initial fracture from the origin penetrates about 70% of the cross section before it slows down as the crack approaches the opposite face. Fracture is completed only when the elastic waves reflected off the rod end faces and came back and reached the fracture plane.

In 1957, George Irwin (Figure 29) revolutionized our understanding of the stresses and strains near the tip of a static crack. His work led to what is now known as the field of fracture mechanics. A superb 1997 book, compiled on the anniversary of his 90th birthday, has a biography and a remarkable series of articles by experts in the field of fracture mechanics. They describe Irwin’s breakthrough and the subsequent evolution of the field of fracture mechanics which was controversial in the beginning. There also are articles about Griffith and Weibull and their influence on Irwin. The effects of external stresses, crack dimensions, and specimen shape are contained in the stress intensity factor, K. The symbol K was named in honor of his colleague J. A. Kiss; and the symbol, G, for strain energy release rate, was chosen in honor of A. A. Griffith. The stress intensity factor is directly related to the strain energy release rate and also the fracture surface energy. Fracture occurs when the stress intensity factor for a crack in a body reaches a critical value, Kc, also known as the fracture toughness. It was no longer necessary to be concerned about the exact peak stress (a singularity) at the tip of a sharp crack. Engineering compilations are available which show tables or equations for Kc for a
Figure 29. George Irwin (1907 – 1998), the founder of modern fracture mechanics. (Courtesy of the Clark School of Engineering, University of Maryland.)

variety of cracks and specimen shapes. Some materials have rising $R$-curves such that the fracture resistance varies with crack size and crack extension due to crack interactions with microstructure.

The advent of modern fracture mechanics in the 1960s had dramatic influences on fractographic analysis. More rigorous mathematical analysis could be applied to cracks of various sizes and shapes, in various loading conditions and stress states and it was no longer necessary to worry about estimates for the crack tip radius and stress concentration factors. One of the most important works on stress intensity shape factors was by Newman and Raju in 1979. They developed an accurate empirical formula for the $K_I$ factors for semicircular and semieliptical surface flaws in beams in tension and flexure. This is a classic engineering problem. Many cracks such as machining grinding cracks may be modeled by semieliptical surface flaws, so their solution was very helpful. Prior to their work, there were a number of conflicting and incomplete stress intensity factor solutions. Fractographic analyses using stress intensity factor analyses have largely replaced analyses using fracture energies. An added impetus for the adoption of fracture mechanics was finding that slow crack growth velocities are strongly dependent upon the stress intensity factor.

Poncelet, a Belgian-American metallurgical engineer, wrote papers in French in 1939 and in English in 1958 on the fracture of glass. These offered explanations for overall fracture patterns and some of the markings on fracture surfaces. His 1958 paper showed how crossing Wallner lines could be analytically modeled to give improved estimates of crack velocities. He also showed “ripple pairs” that are now known as “gull wings” from bubbles in glass, tempered glass markings, and electron micrographs of various regions inside a fracture mirror. He believed that an advancing crack moved forward as an uncoordinated series of jumps all along its front separating the breaking bonds from the lagging bonds. Superimposed elastic vibrations interact with the crack front and cause ripples and undulations. Major redirections of the stress field caused striations to form in the direction of crack propagation. It is worth noting here that many in the early literature used the term “striation” to describe such lines. The term “striations” may be confused with fatigue crack growth markings observed in metals, so it seems reasonable to use the alternative term “hackle” instead, as Preston suggested in 1926.

In addition to all the work being done in universities, some large glass companies were contributing to the science of fractographic analysis, but not all of their work was published. In 1936, Leighton Orr (Figure 30) began a thirty-six year career at the Pittsburgh Plate Glass (PPG) company as
Figure 30. Leighton Orr, who worked for many years at Pittsburgh Plate Glass. (Reprinted with permission ASME.)

Figure 31. Orr's graphs of breaking stress versus mirror radius. The inserts show how to measure the radius in plates tested in pure tension or bending. (Reprinted, with permission of ASTM Int., 100 Barr Harbor Drive, West Conshohocken, PA, 19428.)
A History of the Fractography of Glasses and Ceramics

Figure 32. Orr’s Figure from his 1972 paper for a barium crown glass. Notice equation 2 is shown on the bottom right. (Reprinted with permission of ASTM, Inc.)

head of the Physical Testing department of their research laboratory. He was unable or unwilling to publish much during his career, but upon the year of his retirement in 1972, he had one notable short publication about practical analysis of fracture in glass windows.\textsuperscript{67} Figures 31 and 32 show two of his figures. This paper has a number of useful practical tips on testing and examining broken annealed or tempered plates. It also has some intriguing observations such as a minimum stress of 10 MPa is necessary for cracks to develop mist, hackle, or to branch. This is an interesting observation and was verified by the work of J. Quinn\textsuperscript{68} twenty-seven years later. Orr’s paper also has extensive practical information and data on the measurements of fracture mirror sizes and how to use the basic relationship relating the mirror radius to the stress at the origin at the instant of fracture. Orr’s advice on how to interpret non circular mirrors and how to measure the mirror radii in tempered plates is especially valuable. On the basis of a review of the literature, plus conversations and correspondence\textsuperscript{69} this author had with Orr, it became apparent that Orr was using the now standard relationship for stress and mirror size as early as 1942:

\[
\sigma R^2 = A
\]

where \( R \) is the mirror radius, \( \sigma \) is the stress at the origin and across the mirror, and \( A \) is a constant known as the fracture mirror constant. This relationship has tremendous practical value, and there is nothing like it for metals fractography. It is not necessary to have prior information about how the
specimen was loaded. A small mirror is proof that the specimen was strong and had a small strength-limiting flaw. Conversely, large mirrors mean the failure stress was low and there was a large flaw. In some instances, a specimen may be so weak that the mirror size is larger than the part cross-section, and hence the mirror markings are not visible. That, in and of itself, is valuable information. In other words, the existence of a mirror boundary means that the part was stressed to a moderate or high level. This knowledge was disseminated at various glass conferences such as the Bedford, Pennsylvania meetings of the American Ceramic Society in the 1950s. Relationships similar to eq. 2 were in use by many authors in the 1950s and 1960s, but with different exponents for the mirror radius term. Orr was the first to systematically use the equation with the one-half power to solve practical problems. He also recognized how residual stresses (as in tempered plates) altered the relationship, such as shown in Figure 32, and used that to practical advantage too. I did a careful review of the literature pertaining to fracture mirror size analysis in 2006, and I concluded that eq. 2 should be deemed "Orr's equation." Although many associate eq. 2 with Johnson and Holloway in 1966, the relationship was already in use for over 15 years. Their primary contribution was to use an energy analysis to give some theoretical underpinnings to the equation. After he retired, Orr did a great deal of consulting and prepared 950 failure analysis reports from 1972 until 2003 when he was 96 years old. These reports were donated by Orr to the University of Pittsburgh before his death in 2004. They were intended to be accessible to students and historians. Orr's colleagues arranged for these reports to be scanned and converted to digital PDF format. The reports are a treasure trove of practical information, and include notes on minor and major cases alike. For example, there are many interesting observations about the

Figure 33. Orr showed the fracture surfaces of plates, (a) broken in bending; (b) broken with thermal stresses; and (c) broken tempered glass. (Reprinted with permission of ASTM, Int.)

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\(^{a}\) In January 2009, I went to the Brevick Engineering Library of the University of Pittsburgh and was disappointed to learn that the reports were not cataloged and they did not know where they were. On further investigation with the Director of Development for the Swanson School of Engineering, it was learned that the original paper reports had been removed to archives. They were not accessible to students or investigators such as me. Ms. Sonia Gill, Director of Marketing and Communications of the Swanson School of Engineering did kindly furnish me a CD with digital copies of the files.

failures of the hundreds of large windows in the John Hancock skyscraper building in Boston in the 1970s. An American Society for Mechanical Engineering web site has an obituary-summary of Orr’s life and has an award in his name.

Figure 34. Dr. Frederick Emsberger (1920 - 2003) of PPG proved the existence of the elusive microscopic Griffith cracks. The image on the right shows his 1970s monograph on Polarized Light in Glass Research. The photo of Emsberger is from inside the book. His proof that Griffith cracks existed actually came decades after Frank Preston had shown photos of large Griffith flaws on fracture surfaces in glass. (Courtesy of F. Emsberger.)

Another PPG researcher, Dr. Fred Emsberger, shown in Figure 34, joined the company in 1955 and by 1960 did classic scientific experiments on glass that finally detected the elusive submicroscopic Griffith flaws. He used an ion-exchange treatment with lithium and potassium nitrates to create a differential thermal expansion strain that caused cracks to run stably from starter sources, as shown in Figure 35. A small uniaxial stress was superimposed on the plate so that the cracks grew in a preferred orientation, as shown in the figure. The starter source cracks were in fact minute Griffith flaws that manifested themselves as tiny kinks in the longer thermal expansion cracks. The ion exchange treatment effectively highlighted the 25 nm to 30 nm wide Griffith cracks. The interpretation was confirmed by electron microscope examination of replicas. The cracks were made even larger by the acid etching so that they could be photographed. Emsberger said that the:

“origins seem to be simple straight Griffith cracks; sometimes the crack is crescent shaped or a ‘star’ with three or more arms. All Griffith cracks so far identified appear to have resulted from accidental mechanical injury.”

Emsberger continued working on mechanical properties of glass and wrote several enjoyable reviews such as References 74 and 75. He reviewed all flaw types in glasses in 1974 and categorized them as internal (which rarely cause fracture), surface, or edge. Surface flaws can be from mechanical damage or from chemical flaws. Short biographical sketches of him are in Reference 75 in 1977 and in his monograph on polarized light in glass research.
A History of the Fractography of Glasses and Ceramics

Figure 35. Figures from Emsberger's 1960 Proc. Royal. Soc. London A paper.22 (a) shows long horizontal shrinkage cracks propagated from the tiny initial Griffith flaws which manifested themselves as small kinks, as marked by the arrow. The axis of the tensile stress was top to bottom in this view. (b) shows a pair of cracks propagated in opposite directions from a single origin (arrow) under the influence of uniaxial stress, the axis of which was rotated 90° at 1 minute intervals. (Reprinted with from the Royal Society of London.)

Figure 36. Errol Shand (1893 – 1976). (Courtesy of S. DeMartino, Corning, Inc.)

A third industrial scientist from this era was Errol Shand of Corning (Figure 36) who wrote a number of papers on strength and fractography of glass from 1954 to 1970.77,86 in 1954, he expanded the Wallner lines analyses for crack velocity analysis to rectangular beams in bending.77 He showed how cracks that might reach terminal velocities very quickly after propagating from a surface origin, but then slow down to only 5% -10% of the transverse wave velocity as the crack reaches the initially
Figure 37. Shand’s 1964 illustrations for mirror size (reference 80). (a) shows the correlation of the fracture stress to the mirror width with an insert showing the size should be measured just below the external surface, and (b), how to measure a mirror in a high-strength glass rod for an origin on the side, not at the peak stress location. The stress at the origin location should be used. Notice the mist and hackle regions are shown in the insert.

Figure 38. Figure by Shand (1954) showing a partial mirror in a rectangular beam broken in bending. The fracture surface view on the left illustrates hackle lines near the bottom and Wallner line ripples. The section view on the right emphasizes the compression curl.

compression-loaded half of the beam. Shand was also concerned with the time-dependent changes in strength. Many of his mathematical analyses dealt with stress concentrations at the tip of sharp cracks. His equations are similar in form to the fracture mechanics expressions that were developed by Irwin, but Shand never used stress intensity factors in any of his papers. Since many of his final expressions included the crack tip radius, a very difficult parameter to measure or confirm, it was difficult to apply them in practice. He came very close to deriving eq. 2 for fracture mirror size analysis, but settled for a form with the crack tip radius and the mirror width, instead of the radius. 

His 1959 paper on
measuring fracture mirrors had some excellent tips on how to make the measurements in bodies with stress gradients. He distinguished between the mirror-mist and mist-hackle boundaries. Shand also gave recommendations on lighting and on how many radii to measure in different directions. In 1961\(^9\) he showed how a wedge-shaped tungsten carbide indenter tool could be used to make controlled cracks and scratches, a technique that would be widely used with Vickers and Knoop hardness indenters in later years. Papers in 1964\(^6\) and 1967\(^7\) recapitulated some of the earlier work, but also added some useful sketches of scratch-induced cracks, more guidance on how to measure fracture mirrors, and an interesting discussion of how to treat elliptically shaped flaws to compute an effective flaw size. An interesting testimonial to Errol Shand is on-line as Reference 82 which summarizes his career. It also notes that an award in his name has been set up by the local chapter of the United Way, a charitable organization. It states:

"A personal glass testing laboratory in his home basement enabled him to make accurate studies of breakage phenomenon, and his judgment was much sought after in damage suits involving glass. His laboratory and library were bequeathed to Alfred University in New York State."

A. HIGH STRESS  B. MEDIUM STRESS

C. EDGE BREAK  D. ELONGATED SCRATCH  E. TEMPERED GLASS

Figure 39. Shand’s illustrations of various mirrors in beams in bending from Reference 81.

(a)

(b)

Figure 40. Shand’s 1964 figures showing scratch-scoring type flaws.\(^8\) (a) shows an end-on, cross-sectional view underneath a scored surface on the top. (b) shows side views underneath a scratch.
VAN FRECHETTE AND THE 1960s

One of the most influential brittle materials fractographers, Prof. V.D. Fréchette of Alfred University (Figure 41), began to write on the topic in 1965, halfway through his career. His paper discussed the nature of fractography and the techniques and goals of observation of the fractured pieces. It reviewed classic fracture markings such as the mirror, mist, hackle, gull wings, Wallner lines, river patterns, cleavage, transverse and intergranular fracture in polycrystalline ceramics. Over the succeeding years, Fréchette expanded and refined his nomenclature system (a step that was not without controversy, see Rice's commentary at the end of the paper). Others (e.g., Hull) have used the myriad terms that are used to describe fractographic features, and while there may not be universal agreement to Fréchette's system, it is logical and easy to use. Many of his terms have been adopted in documentary standards. His crowning achievement was the first-ever textbook on fractography of brittle materials, *Failure Analysis of Brittle Materials*, that was published in 1990 at the end of his career. Figure 41 - 43 show several illustrations from his book. This book popularized fractographic analysis and was used to train a generation of fractographers, this author included.

Figure 42. Illustrations from Fréchette's book showing twist hackle. The arrows on the left show how the change in the direction of maximum principal stress causes the crack front to split up.
Figure 43. Figures from Fréchet's book. (a) shows the evolution of primary Wallner lines for a curved crack front advancing from left to right in a glass plate. (b) shows tertiary Wallner lines in a thick glass plate impacted on the lower left.

Figure 44. "Scarps" on a glass fracture surface from Fréchet's book. Scarps form when a crack outruns (or is overtaken by) a fluid or vapor. The direction of crack propagation is from bottom to top.

In 1977, Fréchet began a three-day summer hands-on fractography short course at Alfred University. He trained hundreds of engineers and scientists over the ensuing years. The course continues now as a four-day course, 34 years later. Fréchet and his students James Varner and Terry Michalske used fractographic analysis to study the effects of water on slow crack growth and interpreted "scarps," which are markings on a fracture surface associated with a crack outrunning or being overtaken by a fluid or a vapor as shown in Figure 44. They also studied precracks and running cracks with ultrasonic fractography in fracture mechanics type specimens. Varner described defects in glass from processing and contact damage with superb scanning electron microscopy photos of the latter. Fréchet was also well known for his participation in many court cases, some of which are documented in his book. He was a good oral story teller, and there is a chapter in his book with many fascinating case studies. Some of the cases he described were: "A Tale of Two Teapots," "A Case of Water Hammer," "An Ancient Art Explains a Modern Catastrophe," and "Panic in the Gym." One of his most famous cases involved glue chipping cracks in Boston skyscraper...
windows. In addition to his book and the new fracture surface markings he and his students identified, Fréchet's primary contributions were to popularize fractographic analysis, bring consistency to the analyses, and show how scientific study of fracture solved many practical problems.

Johnson and Holloway (Figure 45) wrote an important paper in 1966 on fracture mirrors in glass. This 1966 work was summarized later in an excellent review article on the fracture behavior of glass by Holloway. They examined eq. 2 in detail and concluded that the hackle boundary is the

![Figure 45. Professor Holloway from Reference 99. (Reprinted with permission of the Society of Glass Technology.)](image)

Figure 46. Fracture mirror figures from Ref. 99. Notice how their schematic drawing does not show the side cusps marked by this author with white arrows in the photo on the left. Kirchner's later analysis accounts for the surface cusps. (Reprinted with permission of the Society of Glass Technology.)

 locus of points at which the rate of release of strain energy by the expanding fracture is sufficient to create continuously four new surfaces and to maintain the finite kinetic energy for the moving cracks. Two of their figures are in Figure 46. They also pointed out that the stress that should be used in eq. 2 is the local stress at the crack front periphery (the mirror boundary) which is not necessarily the maximum stress in the piece or the stress at the origin in the center of the mirror. So for example,
these stresses are the same in a rod loaded in direct tension, but are quite different for large mirrors in rods loaded in flexure. This paper was important at the time since there was considerable doubt as to the correct criterion for the formation of the mirror features. Many had postulated that a critical velocity criterion was the key. This was eventually disproven by various investigators. For example, shortly after the Johnson and Holloway paper was published in 1966, Congleton and Petch\textsuperscript{106} used Wallner line velocity analysis to show that crack branching occurred at various velocities in glass and sapphire. They argued that eq. (2) held in general and, more specifically that:

\[ K_c = \sigma_{\text{cr}} \sqrt{c} \]  
(3)

where \( K_c \) is the critical stress intensity at branching, \( \sigma_{\text{cr}} \) is the fracture stress, and \( c \) is the semi crack length at branching. As will be described below, Kirchner's work in the 1970s and 80s verified that a stress intensity criterion gave much better fit to the actually observed mirror shapes.

Almost twenty years later in 1985, Holloway wrote a fascinating paper: "A Look at the History of Glass Strength."\textsuperscript{44} He credited Griffith's work\textsuperscript{15,17} as a starting point for a review of the strength of glass and commented that:

"Although Preston and Milligan evidently realized the significance of the work, . . . its implications were more often ignored and much that was important or useful in the original paper was soon dropped out of sight."

Holloway lamented about the poor development of the understanding of glass strength in the thirty years after Griffith's two papers in the 1920s.\textsuperscript{44} He referred to the era as the "Dark Ages" and noted that many published papers were of mediocre quality. There were signs of intensive investigations at industrial laboratories that were never reported in the literature. A "Renaissance" occurred in the 1950s as long-range fundamental research was supported at company research and development laboratories and in universities. He cites Emsberger's writings as part of the renaissance.

Scharlin's work on dynamic crack propagation in Freiburg in the 1950s (described above) was continued by Kerkhof in the 1950s into the 1970s,\textsuperscript{101,102,103,104,105,106} Kerkhof, shown in Figure 47, founded the Institute for Solid Mechanics in 1971 which in turn became the famous Institute for Materials Mechanics. This institute was a world leader in the new field of fracture mechanics. Much

\[ K_c = \sigma_{\text{cr}} \sqrt{c} \]  

Figure 47. F. Kerkhof and his 1970 book.
of the work and many illustrations were included in Kerkhof's masterpiece book: Bruchvorgänge in Glasern (Fracture Processes in Glasses) in 1970. Among the many topics this institute studied was the dynamic propagation of cracks in glass. High-speed spark photography work continued, but a new technique "ultrasonic fractography" or "stress wave fractography" was invented by Kerkhof in 1955. A transducer superimposed stress waves into a specimen while the crack was propagating. The slight perturbations to the direction of maximum principle tensile stress caused the propagating crack to form slight ripples (tertiary Walther lines) on the fracture surface. Since the ultrasonic wave frequency was known, it was a simple matter to compute local crack velocities from the line spacings. Figure 48 shows examples. Kerkhof and colleagues were able to use this new approach to measure the terminal velocity of cracks. They also were able to study crack shape evolution with crack extension and interactions of moving cracks with inclusions. Other amazing experiments with high speed photography showed instances where cracks were driven well above the common terminal velocities to supersonic velocities. The use of lower-frequency transducers allowed slower crack velocities to be measured, and Richter and Kerkhof were able to study slow crack growth behavior in glasses. Sommer used optical interferometry microscopy to study "lanes" or hackle and proved that a 3.3 degree rotation in the maximum principal stress was necessary to trigger a lance. A summary of Kerkhof's career may be found on line.

![Figure 48](image_url)

Figure 48. Examples of Kerkhof's ultrasonic fractography. (a) shows markings on a glass fracture surface left by a crack passing by a void. The crack direction is shown by the arrow. The Walther lines created by the external ultrasonic transducer show that the crack locally accelerated as it neared the void, but then slowed around it, but then snapped past the void. (b) shows an accelerating crack that grew from a surface flaw in a bend bar. The evolution of the shape into semielliptical curves of varying aspect ratio is completely accounted for by fracture mechanics analysis. (c) shows a crack accelerating from a notch on the left towards the right. M is for mist and B is for branching. (All courtesy of H. Richter.)
PROGRESS IN MATERIALS SCIENCE IN THE 1970s

Considerable time and energy has been spent over the years on whether cracks in brittle materials experience any plastic deformation at the very tip of the crack. The topic remained controversial for a long time until Hockey (Figure 49) and colleagues in 1975\textsuperscript{110} and 1980\textsuperscript{111} showed that, although dislocation-like features may be present in Si, Ge, SiC, and Al\textsubscript{2}O\textsubscript{3}, the concept of an atomically sharp crack provides a sound basis for the theory of fracture of brittle solids. Figures 50 and 51 show some of his transmission electron microscope images. Later work in the late 1980s with high-resolution transmission electron microscopy by H. Tanaka and Y. Bando confirmed that crack tips in SiC, Si, and sialon were indeed atomically sharp.\textsuperscript{112,113}

In the meantime, intensive studies started in the early 1970s on the relationship between microstructure, strength, flaws, and fracture toughness of polycrystalline ceramics. Many of these studies began to exploit the capabilities of the scanning electron microscope which was becoming more readily available. Advances in ceramic processing led to finer-grained, fully-dense, strong ceramics that were more amenable to fracture analysis. Fractographic markings were clearer and fracture origins could easily be detected.

Figure 49. Bernard Hockey in 2008. (Author’s photo)

Figure 50. Hockey’s TEM illustrations from Reference 110 showing radial cracks segments in single-crystal silicon. Moiré fringes are evident from mismatched portions of the diffracting crystal portions on opposite sides of the interface in (a). (Courtesy of B. Hockey.)
Figure 51. Hockey's TEM illustrations from Reference 110 showing the tip region of a lateral crack in single crystal alumina. There is no trace of microscopic slip. (Courtesy of B. Hockey.)

Henry Kirchner (Figure 52) wrote a number of papers starting in 1973 to 1987 while he was the owner of the Ceramic Finishing Company, a small private grinding shop and testing laboratory in State College, Pennsylvania.\textsuperscript{134,115,116,117} He was particularly interested in the interpretation of fracture mirrors and the mirror size-strength relationship. He and his colleagues published many of the first fracture mirror images and mirror constant values for polycrystalline ceramics (e.g., high strength aluminas, silicon nitrides and silicon carbides) as shown in Figure 53. They showed that not all aluminas or silicon nitrides are alike. Variations in the microstructures led to differences in the fracture mirror constants. In addition to the published journal articles, in 1974 Gruber, Soter and Kirchner published a thick comprehensive Summary Report\textsuperscript{115} on a study done for the US Navy. The study covered the fracture surface markings, the mirrors, and even the flaws in a large number of alumina, silicon nitride and silicon carbide rods broken in flexure. This 100 page report was remarkable in that it included a huge supplemental appendix that had hundreds of photographs of the

Figure 52. Henry Kirchner (1923 – 2008) (Courtesy of James Kirchner).
Figure 53. Fracture mirrors in 96% alumina, hot-pressed alumina, and hot-pressed silicon nitride from Kirchner, Reference 118.

Entire fracture surface and flaw close-up of every single test specimen. Nothing like this had been published up to that time. Specimens were tested in air, in liquid nitrogen, and at elevated temperature in static load, delayed failure, or impact loadings. The authors even commented:

"Early attempts to identify the flaws at fracture origins were unsuccessful because, in weak bodies, the fracture surfaces are rather featureless and it was frequently impossible to determine which one of several observed flaws had acted as the fracture origin. The availability of stronger bodies and improved fractographic techniques have made it possible to identify the flaws at fracture origins in a large fraction of cases."

They commented that some recent publications had started to show isolated examples of fracture origins and flaws in the ceramic literature, but:

"To some degree these publications are misleading because of the tendency to show outstanding flaws that illustrate particular points. In many cases, fractures originate in regions in which none of the features are outstanding and there is no definitive evidence that any particular feature represents the critical flaw."

These comments underscore three important milestones in the 1970s on the history of the fractography of ceramics:

1. Ceramics were being made stronger, often by hot-pressing. Therefore, fracture surfaces became easier to interpret. Discrete flaws could be found.
2. Scanning electron microscopy made it possible to photograph and characterize small flaws and even measure their sizes.
3. Flaw sizes could be compared to calculated flaw sizes based on fracture mechanics.

Most practitioners were by this time using Orr's equation (eq. 2) to analyze their data, but Kirchner was not satisfied. Distortions from the classic circular or semicircular mirror shapes were commonly attributed to stress gradients, but simple adjustments to account for the local stresses failed to account for the actual observed mirror shapes. In addition, stress adjustments could not account for the small cusps located at the surface of a fracture mirror that started at a surface flaw. Eventually Kirchner teamed with the fracture mechanics expert Prof. J. Conway at Pennsylvania State University.
and they published two definitive companion papers in 1987. As shown in Figure 54, these showed that the actual shape of fracture mirrors in tensile or flexurally loaded rods was fully accounted for by a branching stress intensity factor criterion, rather than the more simple stress–mirror radius, Orr's equation. The stress intensity shape factors for semieliptical surface flaws in bending or tension were instrumental in Kirchner and Conway's analysis. Although a full accounting for actual mirror shapes and sizes was now possible, most practitioners continue to use Orr's simple equation since it is accurate for small mirrors in uniform tension or very gradual bending stress fields. It can be used as an effective approximation for many other configurations. I wrote a review of the history of fracture mirror analysis and used it as a basis for a standard for fracture mirror size analysis. Kirchner also published extensively on other polycrystalline ceramic topics such as slow crack growth markings, flaw sizes and shapes, the effects of grinding and single-point scratching on strength. An obituary on Kirchner is accessible online.

Figure 54. Kirchner and Conway's figures from Reference 117 compared fracture mirrors in glass rods tested in bending to predictions based on fracture mechanics that took the stress gradient and the expanding crack front size and shape into account.

One of the most productive teams ever was R. Rice, J. Mecholsky, Jr. (shown in Figure 55), S. Freiman, and their colleagues at the Naval Research Laboratory (NRL) in the 1970s. They produced an impressive body of publications and advanced the state of the art of fractographic analysis through the correlation of microstructure, flaw characterization, mechanical properties, and fracture mechanics. Roy Rice spent much of his forty plus years career investigating the relationship between...
processing, microstructure, flaws, strength, and fracture toughness. The team did research on many topics, and their papers were well illustrated. For example, they studied fracture mirror constants for a wide range of glasses and ceramics. They noted that the mirror sizes were a multiple of the flaw size in many glasses and ceramics. Figure 56 shows one of their famous schematics of a fracture mirror, where in this instance, the prospect of the initial flaw growing due to slow crack growth is noted.

Figure 55. Roy Rice (1934 - 2011) (Courtesy of Craig Rice.), left, and Jack Mecholsky, Jr right (Courtesy of J. Mecholsky).

Figure 56. Schematic of a fracture mirror showing several mirror and branching boundaries, but also stable crack extension from the initial flaw. This figure was used in several papers to discuss the mirror to flaw size ratios. (Courtesy of J. Mecholsky.)
Figure 57. A typical graph of breaking strength versus fracture mirror size illustrating that Orr's equation, equation 2 of this paper, was applicable over a very broad range of strengths, mirror sizes, and specimen types including uniaxial and biaxial stressed test specimens. (Courtesy of J. Mecholsky.)

Figure 58. Mecholsky, Freiman and Rice\textsuperscript{726} showed that a general trend exists for the fracture mirror constant to be a multiple of the fracture toughness (a), or the elastic modulus (b).
Rice, Meckolsky, and Freiman identified many different flaw types in ceramics. Of special interest was the effective fracture toughness at the scale of the flaw and the microstructure and the effective fracture energy or fracture toughness for flaws at the appropriate microstructural level. Figure 59 shows that with coarse-grained materials, the critical flaw may be within a single large grain and the single-crystal fracture energy or fracture toughness is applicable. On the other hand, with smaller grain-sized materials, flaws are often a multiple of the grain size and a polycrystalline fracture energy applies. The strength - grain size trends will therefore vary depending upon the flaw to grain size ratio. A transition from single-crystal to polycrystalline fracture toughness controlled behavior occurs when flaw sizes are comparable in size to the grain size.

Figure 60. Schematic of grinding cracks from Reference 136.
Figure 61. Grinding flaws in mullite from Reference 136. A and B show short transverse cracks that occur perpendicular to the grinding direction, and C and D show longitudinal cracks that are parallel to the grinding direction. These are usually more deleterious to strength. The difference in flaw size and shape account for the directionality of strength in test pieces: bend bars ground parallel to their length (i.e., longitudinally ground), are stronger than bars ground transversely to their length.

This team also wrote a fine series of papers on the nature of grinding cracks and their directionality. They showed that the grinding cracks penetrated far deeper beneath the surface than the grinding striations (confirming Preston’s conclusions), and that the size, shape and severity of grinding cracks were different for cracks parallel or perpendicular to the grinding axis. Figure 60 shows a schematic of cracks that can occur from grinding in a superbly illustrated paper by Rice and Mecholsky. Figure 61 shows actual examples for mullite. The paper also shows several dozen grinding flaws for a variety of ceramics.

Eventually this team dispersed. Freeman turned to management duties at the National Institute for Standards and Technology (NIST). Mecholscy went to Sandia National Laboratory, then Pennsylvania State University, and finally to the University of Florida. He investigated many fractographic topics including structural ceramics fracture origins, quantitative analysis, fractal analysis, single-crystal behavior, slow crack growth effects, manatee bones, and dental ceramics.

Rice retired from NRL and worked at W.R. Grace in the 1980s until he retired. He continued to investigate microstructure-property relationships. Figure 62 is from his keynote presentation on intergranular versus transgranular fracture at the third Alfred Fractography conference in 1995. Rice was a prolific writer. His memorable “Ceramic Fracture Features, Observations, Mechanisms, and Uses” was an astonishing book length (99 pages) paper for a 1984 ASTM conference. It had a wealth of information about ceramic fracture features and was very well-illustrated. An even longer 182 page article, “Microstructure Dependence of Mechanical Behavior of Ceramics” was published in 1977, but had far fewer illustrations. In 1998, near the end of his career, Rice summarized much of this in his book on porosity in ceramics and a second book in 2000 on grain- and particle-size effects.
on mechanical properties. He discussed the value of fractographic analysis in his 1977 treatise paper on mechanical properties of ceramics.

"The most significant experimental procedure that can aid the understanding of mechanical properties is a study of fracture surfaces, especially to identify origins... It is indeed amazing the number of mechanical properties studies conducted that were extensively concerned directly or indirectly with the size and character of flaws and microstructure from which failure originated in which no attempt was made to experimentally observe and verify the predicted or implied flaw character."

![Diagram](image)

Figure 62. Percent intergranular and transgranular fracture versus grain size from Rice's Ref. 139.

Rice’s papers often distilled information from many sources in a quest to find general trends. A distinctive trait of his papers was complex summary figures such as Figure 62. He was meticulous and thorough, and he ferreted out much useful data from a myriad of sources. He expected no less from others, and woe to any oral presenter at a conference who was not prepared. Roy could be counted on to speak from the audience during the question-and-answer period and admonish the speaker for not being aware of an obscure reference.

Roy passed away on April 29, 2011 as this article was being written. I appreciate the many pictures that he gave me, particularly of single-crystal fracture mirrors that are included in my Guide book. After he retired in the 1990s, Roy spent many hours in the basement of the NIST library in Gaithersburg, digging through the archives for data on strength versus porosity, fracture toughness, or grain size. He used my office at NIST as a staging area for these forays, and I benefited from many interesting conversations. An obituary on Rice is on the American Ceramic Society web site.

PROGRESS FROM 1970 - TODAY

Throughout the 1970s and 1980s, thousands of papers appeared with some degree of fractographic analysis. Some of the more systematic studies were done by laboratories and engineering firms that were refining ceramics for use in structural applications such as heat engines. Notable work during this era was done by Muoz et al. and Richerson. There has been progress on many fronts
in the last decade and space limitations preclude mentioning more than just a few studies. A noteworthy recent paper about bioceramics was presented by Richter. A similar article appeared in the last Alfred Conference series book. After a review of ultrasonic fractography, it showed a number of ceramic hip joint ball fracture examples.

One of the current leading teams is Prof. K. Uematsu and S. Tanaka and their students at Nagaoka University in Japan. They have studied the formation of flaws in sintered ceramics by careful fabrication, innovative microscopy, microstructural analysis, and fractographic analysis.

In recent years, I have collaborated with Drs. S. Scherrer and J. Quinn to solve challenging problems in the dental ceramics field.

A team of Austrian researchers at the University of Leoben led by Prof. Robert Danzer has effectively applied fractographic analysis to solve many fascinating engineering problems. Prof. Danzer, Monika Hangel, Tanya Lube, Walter Harrer, and Peter Supanic, have written a number of articles for the Alfred Conference and Slovakian Conference series described below.

New fractography tools have great promise to further expand our field and lead to new discoveries. These include but are not limited to atomic force microscopes, digital camera-microscopes, optical profilometers, computer programs that can create virtual three-dimensional images, programs that interpret roughness and fractal dimensions, and programs and microscopes that overcome the depth-of-field limitations of optical lenses. As an example, Atomic Force Microscopes have led to new insights about fracture mirrors in glasses and are an interesting complement to electron microscopy. In my new area of interest, digital laser scanning of dental prosthetics is routine. Virtual three-dimensional models of structures can be tilted, rotated, manipulated and viewed from any perspective. At present, their resolution is not sufficient to record fine detail such as subtle Wallner lines on fracture surfaces, but it may not be very long before they do.

BOOKS ON FRACTOGRAPHY

Books specifically written on fractography of brittle material were rare until the 1980s. Kerkhof's book Fracture Processes in Glasses was published in 1970. Volume 1 of the Fracture Mechanics of Ceramics conference series organized by Prof. Bradt in 1974 was subtitled "Concepts, Flaws and Fractography." It had nine interesting papers on fractography including contributions from Ernsberger, Rice, Kirchner, and Richterson. A 1982 ASTM conference proceedings on ceramic and metal failures had nine superb papers, including Rice's 99 page article. It also has a fascinating set of comments and recommendations by a panel of experts. Frechet's 1990 book was a milestone and a masterpiece. Bradt and Tressler edited a book Fractography of Glass in 1994 that was a compilation of eight papers. Hull's 1999 book Fractography, a masterpiece with a superb layout and outstanding illustrations, is about fractography in general, and ceramics and glasses share space with metals and polymers. Morrell's Guide to Fractography of Brittle Materials is a concise useful starting point for any aspiring fractographer, and it has some fascinating practical examples.

Conference proceedings books from the quadrennial Alfred University conference series on Fractography of Glasses and Ceramics were first published in 1986 by Professors Frechet and Varner. The present conference is the sixth in the series. The proceedings series are an impressive compilation of some of the best fractographic work in the last 25 years. A European conference series was organized by Prof. Jan Dusza of the Slovakian Academy of Sciences, Kosice, starting in 2001. In 2013 there have been three conferences with proceedings books so far, and a fourth is planned for 2013.

My Guide to Fractography of Ceramics and Glasses was the first to be printed in color on glossy paper and the first available in digital form. There are 725 figures and schematics, such as...
Figure 63. Two figures from the author's guide book. (a) shows a glass rod broken in flexure. The alignment and illumination were meticulously adjusted to show the compression curl, hackle lines, the fracture mirror, and even the flaw itself. (b) shows a silicon nitride rod also broken in flexure. Even at this low magnification, vicinal illumination revealed a telltale "V" shape in the mirror at the origin site. This is a telltale sign that the fracture origin was machining cracks from transverse grinding.

Figure 63. Most had not been published before. The Guide introduces some new terms, markings, and characterization procedures. The book has a strong practical slant. New terms such as "corner hackle," "T-crack intersections," and many dozens of carefully drawn schematics will help the next generation of fractographers learn our craft. The book has been widely disseminated and it is free. It is used in several courses including the annual summer 4-day short course Fracture Analysis of Glasses and Ceramics at Alfred University and the annual summer 3-day American Dental Association Foundation course on Dental Materials Fractography.

FRACOTOGRAHY STANDARDS

In my experience, documentary standards are developed once a discipline has matured to the point that some consistency in procedure is needed. In the late 1970s, I realized that there are two equally important pieces of information that may be gleaned from a strength test: the strength value and the fracture origin flaw. Shortly after we had developed the first standard test method for flexural strength testing of advanced ceramics, MIL STD 1942 (MR),174 I decided that the next step should be to write a standardized procedure for finding and characterizing fracture origins. At that time, fractography was dismissed by some as subjective and interpretive. I spoke on this matter in my paper at the first Alfred conference on Fractography of Glasses and Ceramics in 1986.175 Fréchet14 had taken the first important steps for adopting a common nomenclature, but there was a need for further clarification and refinements.

My colleagues Dr. J. Swab and M. Slavin at the US Army Materials Research Laboratory in Watertown, MA, and I started with a Military Handbook (MIL HDBK) 790 in 1992.176,177 It recommended fractographic analysis procedures and nomenclature for finding and characterizing fracture origins in advanced ceramics. It was a bold step at the time. A fracture origin was characterized by what the flaw was, where it was located, and its approximate size. A simple fracture mechanics analysis was suggested to verify that the appropriate flaw had been found. An atlas of flaw
types was included. We evaluated the MIL-HDBK’s effectiveness with a full scale, seventeen laboratory Versailles Advanced Materials and Standards (VAMAS) international round robin. Lessons learned from the exercise led to the creation and adoption in 1996 of the much more comprehensive ASTM C 1322, Standard Practice for Fractography and Characterization of Fracture Origins in Advanced Ceramics. A comparable European Committee for Standard document for ceramics was written by R. Morrell of the National Physical Laboratory in the United Kingdom in 2004.

In the meantime, in 1993, ASTM C 1256, Standard Practice for Interpreting Glass Fracture Surface Features, written by S. DeMartino of Corning, Inc., was adopted by ASTM committee C-14 on Glass and Glass Products. It is a short, well-illustrated document that describes some classic fracture markings in glass, and uses Van Frechette’s nomenclature.

Over the years, considerable effort has been expended on refining and standardizing test methods for evaluating fracture toughness, $K_I$. Fractographic analysis is a critical aspect of several of the test methods. In 1992 – 1994, Robert Gettings of NIST, Jakob Köhler of the Swiss Federal Research Laboratory (EMPA), and I organized a major VAMAS international round robin on fractographic analysis of precracks in the surface crack in flexure (SCF) test method. Knoop indentations were used to create tiny semieliptical-surface flaws in flexure test specimens. After the indentation damage zones were removed by polishing, the specimens were broken in flexure. The semieliptical-precracks such as shown in Figure 64 were measured on the fracture surface by fractographic methods. Fracture toughness was computed from the fracture load, the precrack size, and an appropriate stress intensity shape factor. Three materials, two silicon nitrides and one zirconia, were evaluated by twenty laboratories. We discovered that the fracture toughness outcomes were surprisingly consistent. Errors or uncertainties in the precrack size measurements had only a small effect on the calculated fracture toughness. This was due in part on the $K_I$ dependence on the square root of the crack size. Furthermore, there was also a curious compensating effect that the stress intensity shape factor, $Y$, errors in crack size were mitigated by a compensating shift in $Y$. The results of this successful round robin led to the adoption of the SCF method as one of three in the fracture toughness standard ASTM C 1421 in 1999 and ISO standard 18756 in 2003. The SCF round robin results also were instrumental in the creation of the world’s first standard reference.

![Figure 64](image)

Figure 64. Fracture surface of a Knoop indentation induced semieliptical surface crack for the SCF method. The test specimen, a hot pressed silicon nitride, that was used for NIST SRM 2100 for $K_I$. 

Fractography of Glasses and Ceramics VI · 47
material for fracture toughness, \( K_{IC} \), NIST Standard Reference Material (SRM) 2106. It is a set of five test specimens with a certified fracture toughness of 4.57 MPa\(\cdot\)m \(\pm 0.11\) MPa\(\cdot\)m at the 95\% confidence level.\textsuperscript{194,195}

My final fractographic standard was ASTM C 1678\textsuperscript{196} for the analysis of fracture mirror sizes in ceramics and glasses, which was adopted in 2008. It was an outgrowth of the Guide to Practice. When I compiled all published results, I realized there was a wide divergence of fracture mirror constants. A summary of my research into this matter and the rationales for the chosen procedures in C 1678 are in my paper at the 2006 Alfred Fractography conference.\textsuperscript{79} Shand, Kirchner, Smekal, Preston, and Orr might have been surprised that such a procedure could be standardized, but I suspect they would be pleased. Rice wrote in 1984.\textsuperscript{140}

“Standardization of the measurement criteria (by analysis of topography for example, to more consistently define the onset of mist and other features) deserves serious attention.”

Controversies will probably continue about fracture mirrors and the basic physics for their formation, but we now have well-defined procedures that will help us solve practical problems and will bring consistency to the field.

CONCLUSIONS

This history is a story of the evolution of materials science, theoretical developments on the strength of brittle materials, the fabrication of stronger materials, advancements in microscopy, standardization, and the key people who developed our craft. Fractographic analysis is an objective scientific discipline that may take time to master, but unlocks the secrets of where, how, and why fracture occurred.

![Fracture surface of a leucite porcelain bend bar processed to have a minimal amount of leucite crystals. The origin is a bubble-pore that almost touched the tensile surface. One can discern the mirror, mist, and hackle, Wallner lines, gull wings from microscopic bubbles and leucite sites. Note how these tiny features trigger early mist well inside the mirror, prior to its general formation for the mirror boundary. (Unpublished, J. Quinn).](image)
ACKNOWLEDGEMENTS

I learned much from the late Professor Van derk Prêchette of Alfred University. I have had many fruitful collaborations and discussions with Professor James Varner, Alfred University; Mr. Roy Rice, NRL; Dr. Roger Morrell, National Physical Laboratory, UK; Prof. Richard Bradt, University of Alabama; and Dr. Susanne Scherrer of the University of Geneva. Finally, I dearly miss Dr. Janet B. Quinn of the American Dental Association Foundation (ADAF). We collaborated on engineering problems for 59 years. She brought a fresh perspective and set of eyes to our field. She had a growing body of publications on fractography analysis, and had she not died so prematurely in 2008, I am sure she would have made great contributions in our field. Figure 65 is a spectacular photo (especially when seen in color) that I found in her files. I continue her work in her memory and acknowledge the support of NIST, ADAF, and the National Institute of Health with NIH Grant R01-DE17983.

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