Fractography of Glasses and Ceramics VI

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These are the proceedings of the Sixth Alfred Conference on the Fractography of Glasses and Ceramics, which was held in Jacksonville, Florida, 5-8 June 2011. Van Fréchette and Jim Varner of the New York State College of Ceramics at Alfred University started this series in 1986.

The Fifth Conference was held six years ago (9–13 July 2006, Rochester, New York), and we felt that it was time to get another snapshot of research and practice of fractography of brittle materials. We asked S. Jill Glass (Sandia National Laboratory, Albuquerque, New Mexico), John J. Mecholsky, Jr. (University of Florida, Gainesville, Florida), and Jeffrey J. Swab (U.S. Army Research Laboratory, Aberdeen Proving Ground, Maryland) to join us as members of the conference organizing committee. We are grateful for their guidance and assistance in attracting speakers and participants. They were especially helpful in identifying conference topics and potential invited speakers. Their active participation in the conference was also one key to its success.

Fractography of Glasses and Ceramics VI had the following objectives: (1) review progress in fundamentals of fractography of glasses and ceramics; (2) highlight applications of fractography in research, production, testing, and product failure analysis; (3) promote discussion among diverse users of fractography of glasses and ceramics; (4) document the state of fractography and its importance in the field of glass and ceramics.

We met these objectives through over 30 high-quality presentations (including four invited papers) and lively, in-depth discussions in the formal sessions and during the breaks. We were pleased to have a mix of experienced fractographers and folks who are newer to the discipline. There were presentations on a variety of ceramics (silicon nitride, alumina, nanocomposites, laminates, dental ceramics, ceria, and zirconia), and glasses. Topics included effects of laser etching of glass, fractography of ion-exchange-strengthened glass, mixed-mode failure, effects on crack evolution and propagation, quantitative fractography, ballistic damage, and effects of processing on strength and fracture behavior. The invited talks provided in-depth coverage of four very different subjects. George Quinn’s keynote lecture was a thorough look at the...
history of the fractography of glasses and ceramics. His careful study of the literature and excellent choice of images made this a fascinating presentation and addition to these proceedings. Matteo Ciccotti provided an excellent overview of phenomena at the crack tip during slow crack growth in glasses. Jan Dusza highlighted failure and damage mechanisms in ceramic nanocomposites. Chuck Kurkjian brought his insights into the issues of inherent strength and damage mechanisms in glasses.

The Sixth Alfred Conference on the Fractography of Glasses and Ceramics met our goal of providing a snapshot of the state of fractography of these brittle materials. We thank our co-organizers and all of the presenters and participants for making this a lively and successful meeting.

JAMES R. VARNER
MARLENE WIGHTMAN
Dedication

Roy Rice

We dedicate the proceedings of the Sixth Alfred Conference on the Fractography of Glasses and Ceramics to Roy W. Rice. Roy passed away on April 29, 2011, at the age of 76.

Roy Rice had a long and distinguished career of research in ceramics. He started with Boeing, later headed the Ceramics Section and Branch of the Naval Research Laboratory, and was Director of Materials Research of W.R. Grace & Co before his retirement in 1994. He published over 300 papers, authored three books, and was granted 30 patents. His research topics include pressure sintering and other processing techniques, machining and its effect on properties, and the effect of porosity on mechanical and physical properties. His colleagues recognized his innovations of concepts, processes, and structure-property relationships. Whenever Roy presented a paper or made a comment at a technical meeting, people listened.

Among his many accomplishments, Roy was a pre-eminent fractographer of ceramics. He was closely associated with the Alfred Conferences on fractography. He gave the plenary lecture, the very first lecture, at the first conference in 1986. The published version of his talk ("Perspective on Fractography") is still used by researchers today who want to gain perspective on failure analysis of polycrystalline ceramics and single crystals. Roy attended every other conference in this series, except this most recent one. His contributions in the published proceedings, like the first one, remain valued references. For example, there is no better summary of
fracture modes in polycrystalline ceramics than his leadoff article in the proceedings of the Third Alfred Conference ("Ceramic Fracture Mode—Intergranular vs. Transgranular Fracture").

These Proceedings will be the first without a paper from Roy Rice. His absence at the meeting was felt, and we sorely miss having another print example of his remarkable insight into the complexities of fracture in polycrystalline ceramics and single crystals. Most of all, we miss his smile, his unassuming nature, his abiding interest in ceramics, and his inherent kindness.

JIM VARNER
Janet B. Quinn, 58, passed away on July 19, 2008 after a brief but valiant battle with lung cancer. At the time of her death, Dr. Quinn was a Project Leader for the American Dental Association Foundation Paffenbarger Research Center. Her research was funded by grants from the National Institutes of Health and the Rockefeller Brothers Fund. Janet began her professional career at the U. S. Army Materials Testing Laboratory in Watertown, Massachusetts, while also rearing her two children. Later, she worked as a consultant at the National Institute of Standards and Technology (NIST). She also became a student again, and received her Ph.D. in Materials Science and Engineering from the University of Maryland 25 years after getting her M.S. in Mechanical Engineering.

Janet’s work included time-dependent failure of ceramics, development of testing methods and programs, determining fracture energies of single crystals, and tensile testing of ceramic fibers. More recently, she turned her considerable intellect and deep scientific curiosity to the field of dental ceramics. In just a short period of time, her studies on dental restoration failure analysis earned her international
recognition. Janet worked hard to hone her own skills as a fractographer. As her experience grew, so did her desire to share her knowledge with others. She developed and led the first dental fractography hands-on course in May 2007 at NIST. Goals of this course included understanding failure modes of dental restorations, producing guidelines and recommendations for improvements in longevity of dental restorations, and making more people in the field aware of available information. Janet drew upon her own experience and her participation in the Alfred short course on Failure Analysis of Brittle Materials in the summer of 2003 in creating her course focused on fractography of dental restorations. She led the course again in 2008, just a few days before receiving the news that she had lung cancer. The course continues to be offered each year and to be well attended, with Janet’s husband, George, carrying on the leadership.

Janet Quinn was also well known outside of science through her accomplishments in Middle Eastern dance. She was a professional instructor of Middle Eastern dance, and she trained hundreds of belly-dance students in Boston, Washington, D.C., Cologne, Germany, and Strasbourg, France.

We know that Janet Quinn would have contributed much more to fractography of ceramics, especially of dental restorations, had she been given more time. However, we celebrate the significant contributions that she made throughout her entire professional career, and we remember her joy of life, her ability to brighten up any room that she entered, her ever-present smile, her affection for people, and the inspiration she provided to everyone who spent even five minutes with her.

Jim Varner
Marlene Wightman
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 metals 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 Emsberger. 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 breakage 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 Stara 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 “Wallner 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
A History of the Fractography of Glasses and Ceramics

Although he showed no pictures, Brodmann\(^8\) 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.\(^8\) 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 failure 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 bitumen. 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\(^9\) and 1914.\(^10\) 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 fracture 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 Brodman 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
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 diametrally-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 Freminville’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 striae. Some illustrations and schematics showed overlapping crack portions that formed hackle lines (lances). 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 Freminville 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 Freminville’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 Freminville’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:

\[ \sigma_f = \sqrt{\frac{2E\gamma_f}{\pi c}} \]  

where \( \sigma_f \) is the fracture stress, \( E \) is the elastic modulus, and \( \gamma_f \) 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.”
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.) 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 work 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. 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.”
A History of the Fractography of Glasses and Ceramics

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

Figure 13. Preston's photos of damage caused by a hard ball. (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 that showed how soft metals could damage glass surfaces by creating chatter slecks 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 perceptive papers on the strength of glass 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 Freminville 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.
A History of the Fractography of Glasses and Ceramics

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.)

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. (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. H 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. Preston replied with further comments on "flaws." In a brilliant anticipation of Weibull's 1939 analysis, he said:

"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}