Griffith's Legacy to Alloy Design and Beyond

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For those of you having had an undergraduate or graduate course in Materials Science it is impossible that you escaped hearing about the Griffith criterion of fracture. Many of us have been so taken by its simplicity that hundreds, if not thousands, of academics have taken a shot at trying to improve it. For that reason alone, we thought it appropriate to have a *Griffith Centennial* this year. The goal of this introduction is to suggest how alloy design has benefited from Griffith's original insight. A brief history of brittle fracture will suffice to introduce how we think history informs the future of alloy design. It will continue to play a pivotal role in alloying and processing aspects to improve structural, transportation, microelectronic, energy, and biomedical properties.

While all of you know of the Griffith criterion and its eventual impact on basic research, you may not know how little impact it had on basic and applied research for the next three decades after his discovery. Particularly, there was little university instruction and industry continued to rely upon the Charpy V-notch test for a standard. One could tell the size of the impact by examining Timoshenko's book from 1941. Here, it was mentioned that Griffith, while admitting that "very fine scratches on glass do not produce a weakening effect" of the material was because there were "internal defects in the glass with just as high a stress concentration factor". The book did mention other authors, namely Sachs, Westergaard, Ludwig, and Th.V. Karman, but that was about it. For those of you whom I have

talked to, mostly at Gordon Conferences and TMS meetings, I thought a brief review of the early thoughts on brittle fracture and subsequent lack of inclusion in important texts for the next 30 years was in order.

Following Timoshenko, there was Nadai's book of 1951, which mentioned all of the above plus Neuber, Orowan, Parker, and Irwin, and demonstrated that a few advances in experimental insight such as electron microscopy and sophisticated test systems for fracture analysis were just in process. (Note: I had to mention Earl Parker as he was my PhD advisor who earned a Presidential Medal for his work on Naval Ships after World War II.) It was not until the Space Race, in the late 1950s, that basic research was able to take advantage of the mainline research establishments at General Electric, Westinghouse, Boeing, and Honeywell, to name just a few, to demand increased funding from the US Federal Government in order to compete with the Soviet expansion. With George Irwin (Naval Research Lab) and Paul Paris (Lehigh and Boeing) as leaders, the ASTM E-24 fracture toughness committee established a fracture toughness standard using Griffith's theory. While this was largely a response to needing improved aircraft and "deeper" space probes, it provided all engineering and basic science an order of magnitude increase in *sophistication*.

The jump in science and engineering careers provided virtually every technical field to participate in the space race. Still, there has never been a broad engineering and science disciplinary symposium based on Griffith's brilliant foresight until now. For the relatively broad field we represent, an appropriate slice of engineering science in all fields has allowed collegial researchers to provide an update of small scale dynamics, expanded temperature and time, and imaging advances. In order to achieve these advancements, sophisticated

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scanning and transmission electron microscopy, and atomistic and mechanics simulations, as well as improved fabrication methods for micro- and nano-sized samples were necessary.

Where does alloy design now stand 100 years later?

We are on the precipice of breakthrough understanding of fracture behavior because of the willingness of all fields to seek us out, as materials scientists and engineers, as collaborators in research endeavors requiring sophisticated instrumentation and testing methods. This is necessitated by the need for experimental and physical insight into the atomistic, chemical, and scale interaction necessities of high-level understanding. How many times have you been approached by mechanical, aero, electrical, or biomedical engineers for material selection insight? What you have seen up to now is miniscule compared to what it will be, and what is proposed here is something you should think about. What I propose here is only for fracture, since it is one of the few sciences that has avoided a more complete understanding sufficient to be awarded a Nobel. Why is that? Think of the variables that require understanding fracture:

- Strength: At least a decade! Factorial for a given alloy with two or three chemistries;
- Microstructure: Complex microstructures 2, 3, or more crystallographies, $([hkl]\{uvw\})$;
- Multiple chemistries: Periodic Table + ions;
- Defect anomalies: Point defects with singular, clustering, radiated, etc., innumerable;
- Rate effects: can affect all of the above; strain rate, thermal rate, environmental rate (H_2);
- Thermal and phase effects;
- Cross-correlated interactions between 2, 3, 4, or more of the above;

Although it would be easy to continue, you probably get the point.

What is suggested here is that one needs to combine the effects that are most the important, knowing that fracture toughness, for example, depends upon an energy release rate, and that the energy release rate can be more easily understood as a rate effect which also includes many of the above effects. There are in the technical literature quite strong proposals that suggest how these effects might interact, and as such there is hope that a better understanding of fracture mechanics with the above technical fields, as well as the advances from micro- and nanoscale testing, will eventually resolve the complexity that has unabashedly left us mystified for a century. But why are we in a particularly promising position to perform a needed contribution to alloy design? All one has to do is to examine what is your next contribution to the literature. It will possibly involve medium or

high entropy alloys, bulk metallic glasses, thin films, or composite materials, as well as reconstituted nanoparticles, or biomedical breakthroughs.

There are three areas of research and development which will make an exponential impact on alloy design. Here, we include both chemistry and processing as intimately interacting to produce increasing combinations of properties.

1. *Properties for infrastructure:*

- *Ultra-high strength* One can have a mile-high building to conserve spacing in dense cities. DeJong, in 2008, designed a mile-high building which proposed to use 2000-kg ropes of carbon fibers for hoisting elevators. This is an order of magnitude lighter than the state-of-the-art ultra-high-strength steel ropes, weighing 27,000 kg, currently used.¹⁻⁸
- *Ductility* Large numbers of papers and reviews of multi-principle element alloys (MPEA) have demonstrated that near-equiatomic alloys with 4–6 elements have excellent strength and extremely high fracture toughness.⁶⁻¹⁵

2. *Properties for outer space and energy solutions:*

- *Low-temperature strength* From near-zero to hundreds of K, resilience of extreme temperature cycling, for long-distance radar acquisition and systems requiring a launch to Mars, as well as satellites require special multi-material designs.^{1,3-5,9,10,12,16,17}
- *Increased fracture toughness* Space travel to Mars, for example, requires high hardness as well as modifications to thwart excessive interaction with space debris and proton bombardment. Future nuclear and fusion reactors also pose material challenges.

3. *Properties for biomedical applications:*^{4,8-11,18-21}

- *Environmental resistance* Corrosion of most implants releases hydrogen, and most alloys are susceptible to embrittlement. Some MPEA compositions might resolve such a problem; however, there has been little research reported in the open literature.²²⁻³⁰
- *Deep brain communications:* From batteries to implants, a necessity is to maintain wire integrity.^{2,4,30-33}

The following contributions are part of those which will eventually help all of us challenge this long-awaited search for the “Holy Grail” of fracture phenomena.

The contribution by Chaudhari et al. provides an interesting computational comparison of different experimental geometries that overcome conventional issues of fracture testing small volumes of material. They indicate that simple changes in geometry can be utilized to investigate if materials

exhibit linear elastic fracture behavior over multiple length-scales. The results of this work could have broad application in examining the science of fracture, and the engineering quality control, needed to provide factors of safety on micro- and nano-scale materials and devices for biomedical and electronic sensor arrays.

One class of alloys that has received attention due to its intrinsic toughening mechanisms are MAX-phases. Using a micro-double cantilever beam geometry (DCB), the delamination and fracture energy along the basal plane was measured of Ti_3SiC_2 by Oriol Gavalda-Diaz et al. These in situ experiments allow for the nanoscale study of crack propagation and the significant role of small misorientations on the fracture energies. Using a similar methodology, Max Emmanuel et al. provide experimental evidence of the fracture toughness variations of different grain boundaries. Although the work by Tejas Chaudhari et al. indicates that this DCB geometry is prone to instabilities, it provides a valuable opportunity to determine if there is sufficient design motivation to promote future grain boundary engineering. The authors motivate their work by assessing the grain boundary strength in tungsten carbide, which, under applications such as cutting tools, is prone to both transgranular and intergranular fracture.

Thin film fracture is another area of interest. The paper from Jie Chen et al. examines the controlled spalling of Ge and the role of mode III loading. Finite element simulations and experimental work also illustrate how the size of the spalling area influences the extent of the visible “riverlines” on the fracture surfaces.

The final paper in this series, by Alexander Leide et al., compares the fracture behavior of irradiated and non-irradiated SiC using nanoindentation. Advanced high-resolution electron backscatter diffraction and Raman spectroscopy were used to measure the residual stresses of the irradiated surface. It was found that fracture can be suppressed due to the swelling-induced compressive stresses in the irradiated material. When the stress is released via focused ion beam cross-sectioning, cracks form in the irradiated material, leading to similar fracture energies such as non-irradiated material.

All titles and authors of the articles published under the topic “100 Years of the Griffith Fracture Criteria” in the June 2021 issue (vol. 73, no. 6) of *JOM*. The articles can be accessed fully via the journal's page at: <http://link.springer.com/journal/11837/73/6/page/1>.

CONFLICT OF INTEREST

None of the authors have a conflict of interest.

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