Statistical failure analysis of crystallographically isotropic brittle porous materials

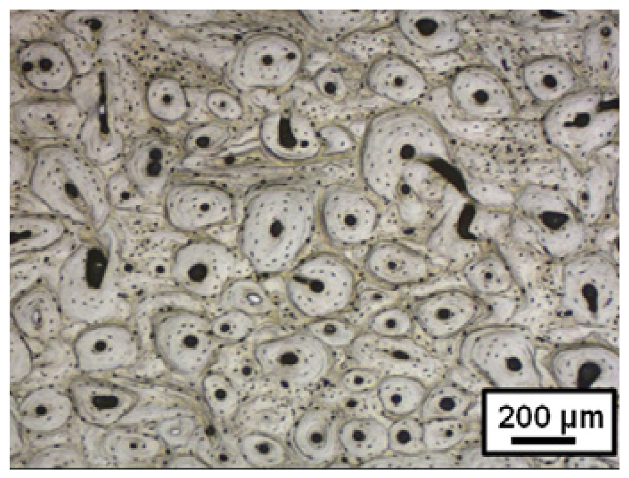
Ozgur Keles[1], R. Edwin García[1], Keith J. Bowman[2]

[1] School of Materials Engineering, Purdue University, West Lafayette, IN

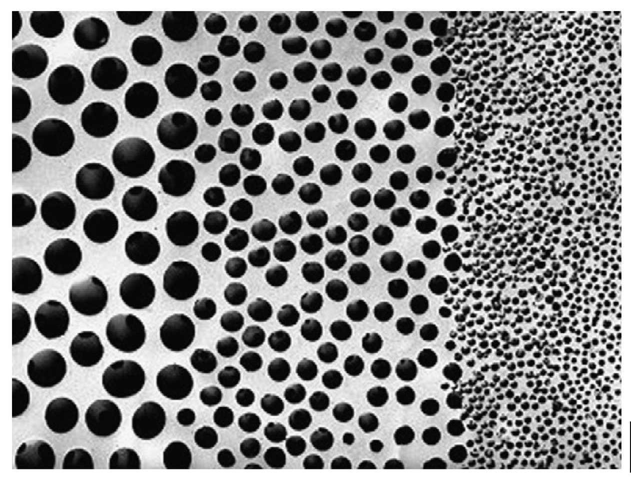
[2] Department of Mechanical, Materials, and Aerospace Engineering, Illinois Institute of Technology, Chicago, IL

Problem: The effect of porosity on reliability and brittle fracture is unclear.

✔ Natural ⟷ Biomimetics ⟺ Artificial ?



[1]

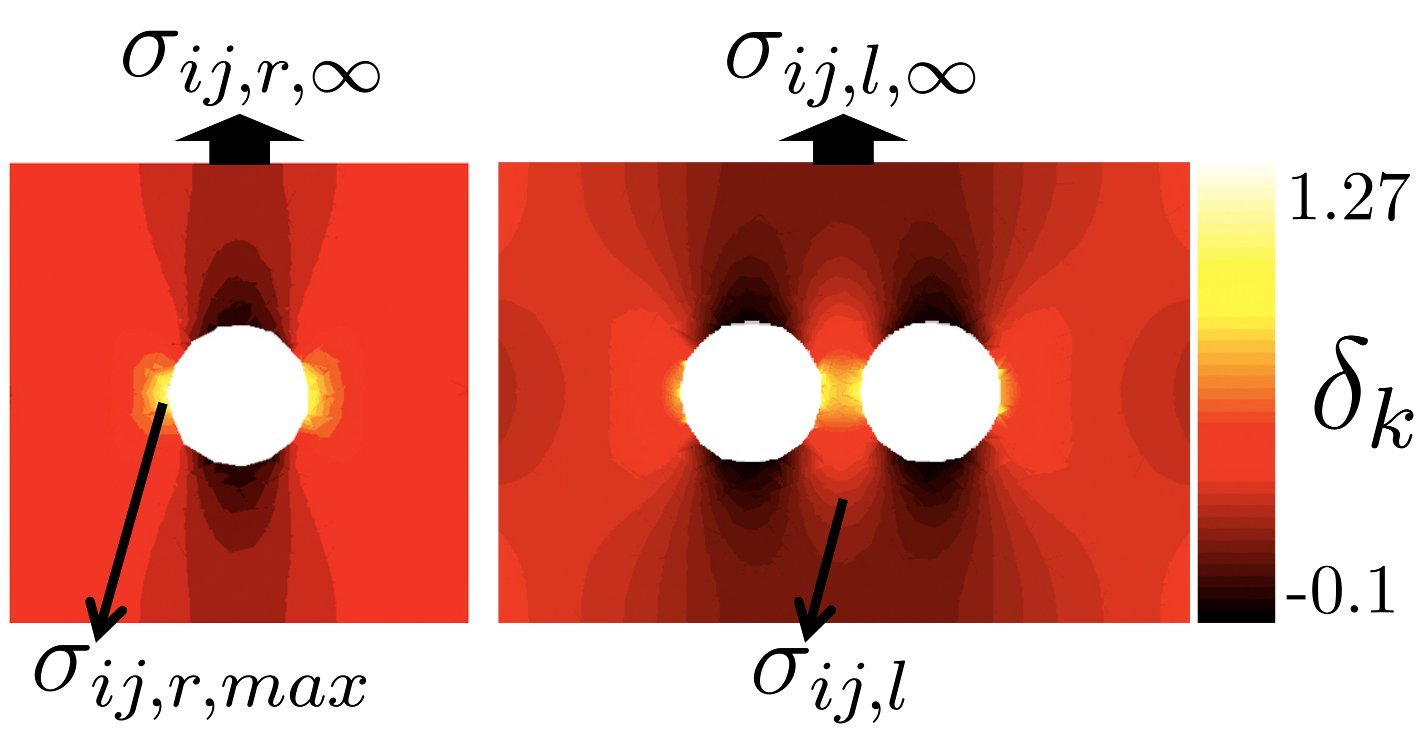

[2]

Theoretical framework: Classical fracture mechanics approach was modified by adding a stress interaction factor, δ_k.

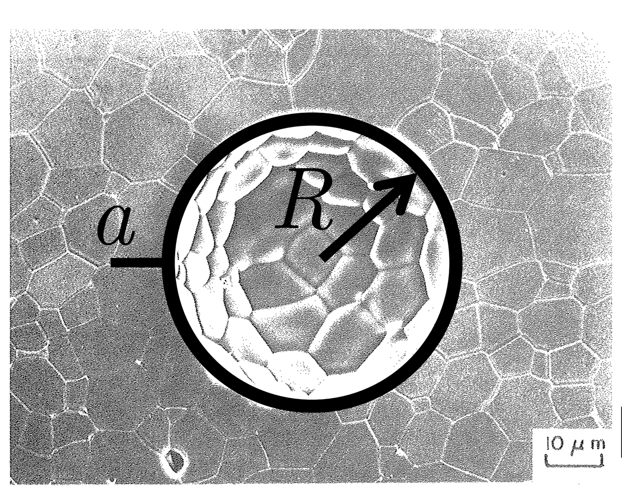
$$\sigma_f = \frac{K_{Ic}}{\delta_k \ Y \sqrt{\pi a}}$$

Stress interaction factor, δ_k:

$$\delta_k = \frac{k_{tl}}{k_{tr}}, \qquad k_{tl} = \frac{\sigma_{ij,l}}{\sigma_{ij,l,\infty}}, \qquad k_{tr} = \frac{\sigma_{ij,r,max}}{\sigma_{ij,r,\infty}}$$



Geometric factor, Y:



[3]

$$Y = Y_2 Y_{12} \ [4]$$

$$Y_2 = 1 + \frac{1}{2\xi^2 + 1.93\xi + 0.539} + \frac{1}{2(\xi+1)}$$

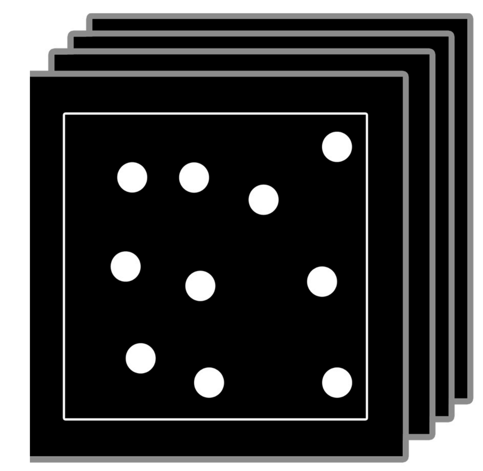
$$Y_{12} = \sqrt{\frac{2+\xi}{2+2\xi}}\left[1 + \frac{0.2\xi}{(1+\xi)^3}\right]$$

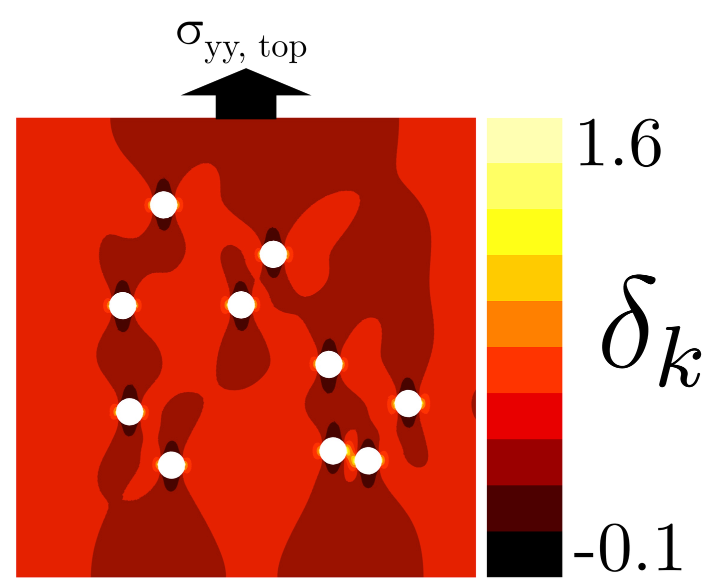
$\xi = \frac{a}{R}$ $\quad a =$ Crack length, $R =$ Pore radius

Assumptions: 1. Crack length is fixed and is equal to the average grain size of alumina, 8.8 µm [3].
2. A crack is present at the maximum stress point.
3. Material fails without any toughening at a fixed K_{Ic}.

Numerical setup: Finite element simulations of 2-D microstructures were done by OOF2 [5] program;

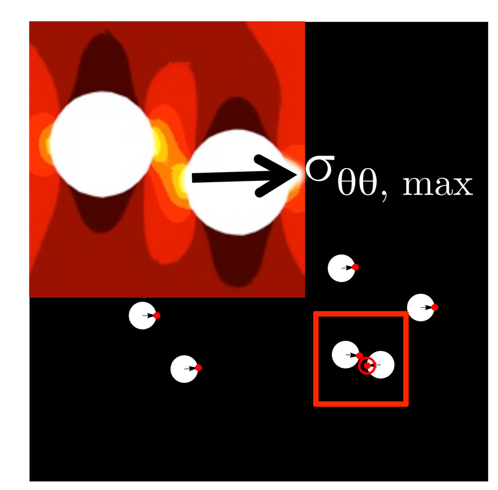
1. Forty different microstructures with fixed number and size of non-overlapping pores were generated. A total of 840 microstructures were simulated.



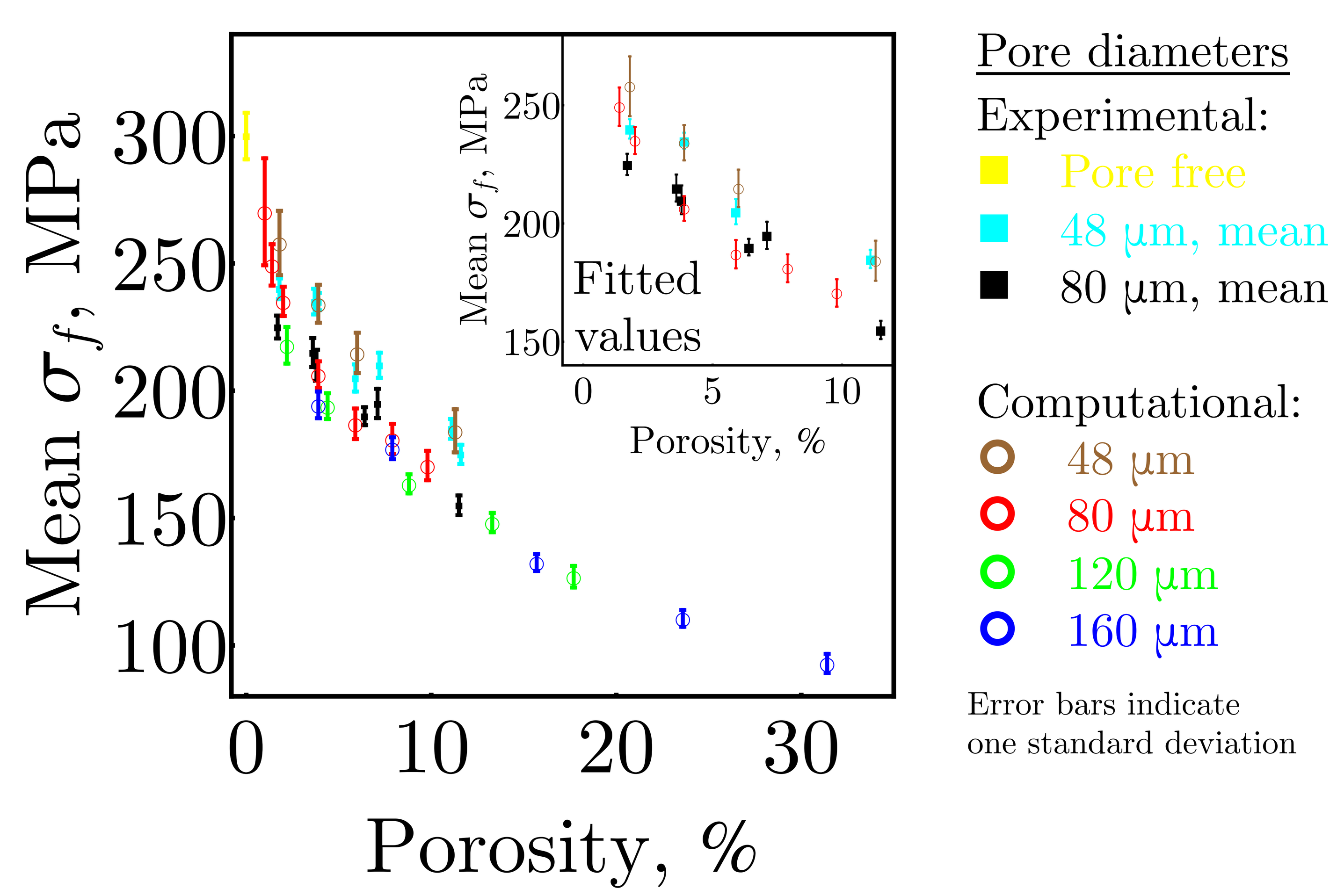


2. Mechanical response simulations were done under uniaxial and biaxial loading conditions.

3. Maximum tangential stress, $\sigma_{\theta\theta,\ max}$, in each microstructure were found. Stress interaction factor, δ_k, was defined by the ratio of $\sigma_{\theta\theta,\ max}$ to the top boundary stress, $\sigma_{yy,\ top}$.

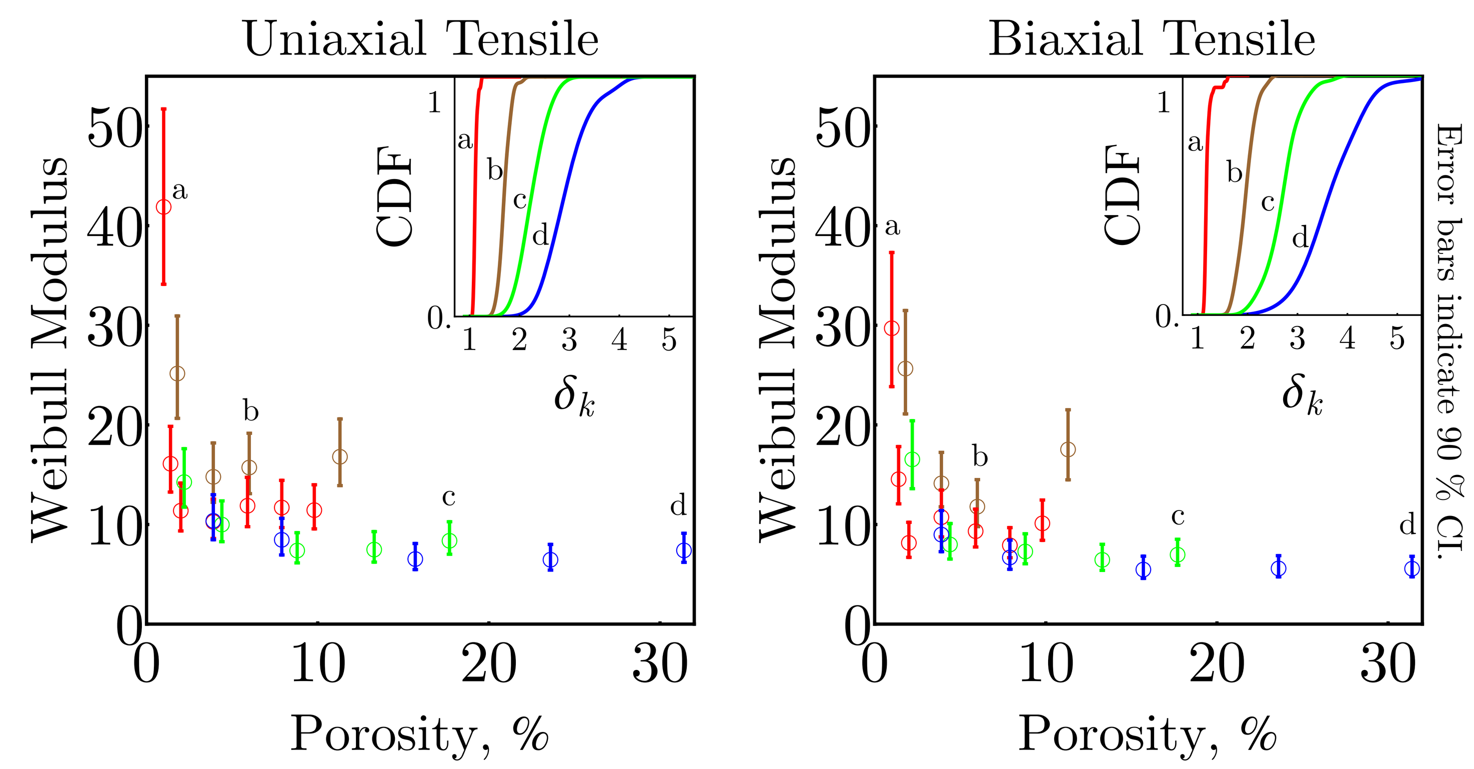


Model validation: The hypothesis that the failure of porous alumina is controlled by the local stress interactions between pores was tested.



- Mean failure stress fits for experimental and numerical values of 48 and 60 µm diameter pores resulted in $K_{Ic} = 3.6$ MPa√m.
- The decrease in mean σ_f with increasing porosity is due to the increasing stress interactions.
- The decrease in $\langle\sigma_f\rangle$ with increasing pores size is due to the larger stress field on the crack of fixed size.

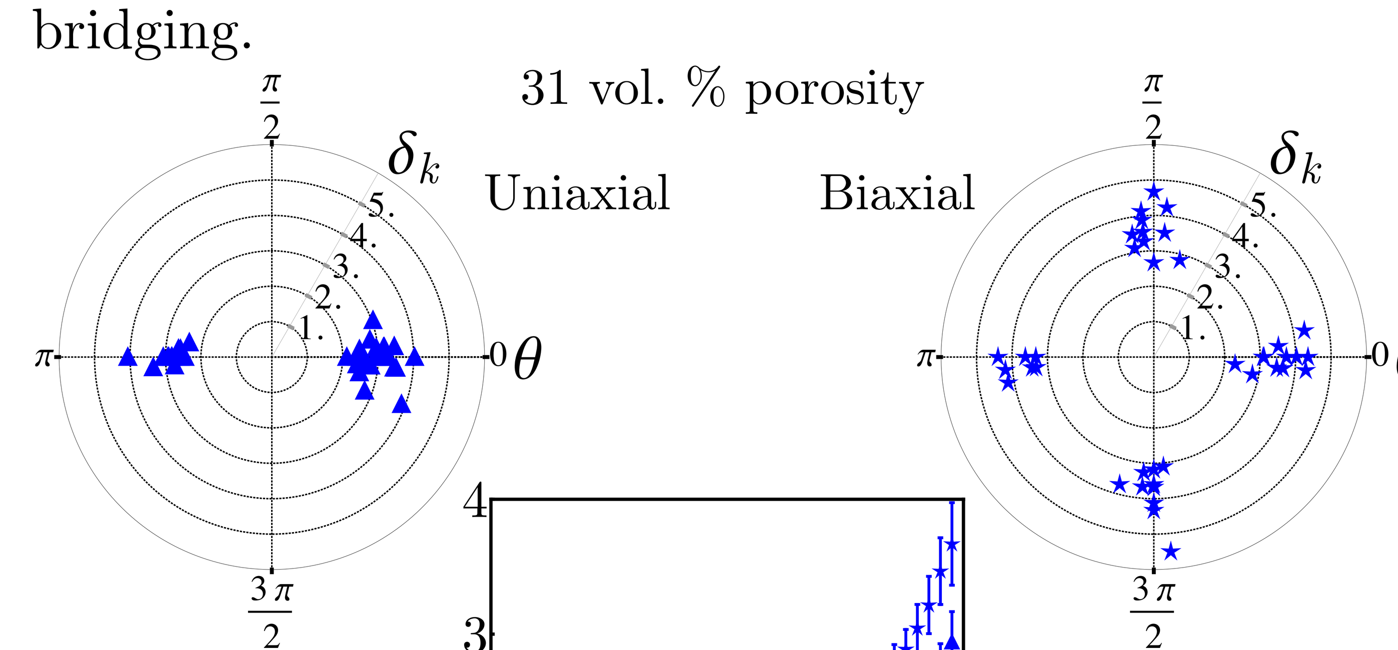
Fracture statistics: Minimum failure stresses for each set of microstructures were fitted to the two-parameter Weibull distribution function.



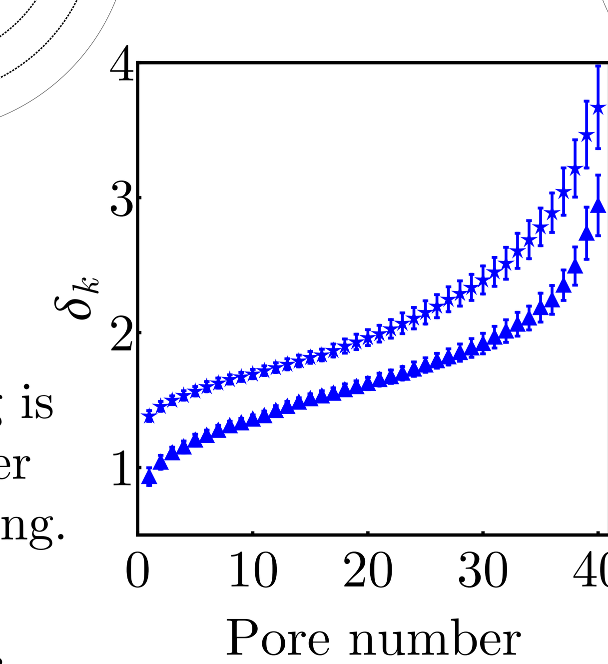
- High reliability is limited by the spatial randomness of the pores.
- Increasing minimum pore-pore distance or/and patterning spatial distribution of pores decrease δ_k scattering; hence, increases reliability.

Future work: Statistics of microcracking and crack bridging.

31 vol. % porosity



- No shielding is present under biaxial loading.



- The scattering at high stresses is wider.

References:

1. E. Novitskaya, P.Y. Chen, S. Lee, A. Castro-Ceseña, G. Hirata, V.A. Lubarda, and J. McKittrick. Anisotropy in the compressive mechanical properties of bovine cortical bone and the mineral and protein constituents. Acta Biomaterialia, 2011.
2. M. Descamps, T. Duhoo, F. Monchau, J. Lu, P. Hardouin, J.C. Hornez, and A. Leriche. Manufacture of macroporous β-tricalcium phosphate bioceramics. Journal of the European Ceramic Society, 2008.
3. J.S. Wallace. Effect of mechanical discontinuities on the strength of polycrystalline aluminum oxide. Master's thesis, University of California, Berkeley, 1978.
4. G.C. Sih, Handbook of stress-intensity factors. Institute of Fracture and Solid Mechanics, Lehigh University, 1973.
5. A.C.E. Reid, R.C. Lua, R.E. García, V.R. Coffman, and S.A. Langer. Modelling microstructures with OOF2. International Journal of Materials and Product Technology, 2009