Failure of notched zirconia specimens under residual stress

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When machining zirconia (Y-TZP) notched samples, honing of the notch causes a phase change from a tetragonal to a monoclinic micro-structure [1] along the surface. The result is a thin layer where a strong compression prevails, up to 1.8 GPa and linearly decreasing in depth until 7–8 µm. Moreover, these residual stresses depend also on the notch root radius ρ, which is one variable parameter of the experiments. They reach a maximum for ρ between 5 and 12 µm. For wider notches with radii above ~ 90µm created by cooled diamond grinding they are significantly smaller [2]. When testing the specimens in 4-point bending, this obviously leads to an apparent increase in strength and toughness.

Experiments were carried out on various specimens with ρ varying from 6 to 90 µm. Two types of specimens were tested, one as sintered and the other having undergone a heat treatment in order to release the residual stresses (heating at 1100 °C for 1/2 hour).

We propose in this work to use the Coupled Criterion (CC) [3,4] to predict this apparent enhancement of the fracture properties and compare with the experiments. Indeed, the CC is twofold, it requires to verify an energy condition, as does Griffith's criterion, but also a stress condition which must be very sensitive to the presence of high residual stresses. Moreover, it does not require the modeling of a prior defect whose dimension could be chosen more or less arbitrarily.

Calculating the residual stresses and solving the elastic problem of bending are carried out separately by Finite Elements and then combined. This separation is made mandatory because of the different boundary conditions in the two problems. Residual stresses due to honing or grinding are obtained using a similarity to thermal residual stresses. A first scalar field is built along the notch surface, taking the value 1 at the surface and linearly decreasing to 0 at a distance of 7 µm. It can be associated with the volume fraction of monoclinic phase and will be used, by analogy, as the temperature field. It is subsequently calibrated so that the compressive residual stress takes the value 1.8 GPa at the surface as reported in [1]. On the other hand the simulation of the 4-point bending loading is standard.

The stress field is first computed on the uncracked structure along the expected crack path (the symmetry axis). Then, a virtual crack of variable length is created by unbuttoning pairs of nodes. For each length, the strain energy is computed, allowing to define the energy function involved in the CC as a function of the crack length. The implementation of the CC amounts to solving two inequalities that provide the critical load causing the failure and the crack length at initiation.

Despite the thinness of the residual stress zone, the comparison with the two cases, thermally treated or not, is conclusive. The CC captures the apparent improvement in the fracture properties of the material in a very satisfactory way.

References

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