Fatigue of Ceramics

It has long been assumed that because dislocation motion in ceramics is limited, strain hardening and consequent crack extension during cyclic loading would not occur, and hence ceramics were not susceptible to fatigue damage. And indeed, ceramics with homogeneous microstructures such as glass or very fine-grained single-phase ceramics do not appear to be susceptible to cyclic loadings.

However, more recently, with the development of tougher ceramics that exhibit R curve behavior, such as transformation-toughened zirconia and whisker- and fiber-reinforced ceramics, it is becoming clear that the situation is not as simple as first thought. Recent data seem to suggest that R curve behavior can be detrimental to fatigue life

Experimental Details: Measuring Fatigue

In a typical fatigue test, a sample is subjected to an alternating stress of a given amplitude and frequency. The cyclic stress amplitude is defined as

$$\sigma_{amp} = \frac{\sigma_{max} - \sigma_{min}}{2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(1)}$$

Whereas the load ratio ***R*** is defined as

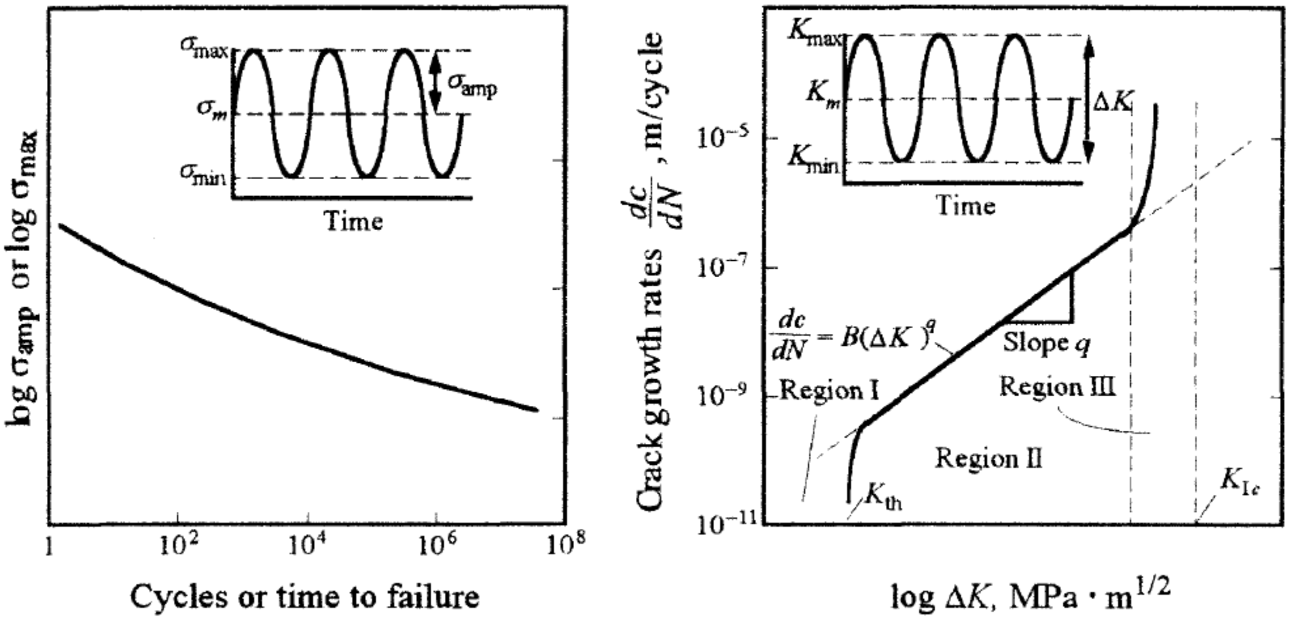
$$R = \frac{\sigma_{min}}{\sigma_{max}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where σ_{min} and σ_{max} are, respectively, the minimum and maximum stress to which the sample is subjected (Fig. 1a). The experiments can be carried out either in tension-tension, compression-compression, or tension compression, in which case R would be negative.

Two types of specimens are typically used, smooth "crack-free" specimens or specimens containing long cracks, i.e., cracks of dimensions that are large with respect to the structural features of the material.

For the smooth or crack-free specimens, the experiments are run until the sample fails. The results are then used to generate ***S/N*** curves where the applied stress amplitude is plotted versus the cycles to failure (which are equivalent to the time to failure if the frequency is kept constant), as shown in Fig. 1a.

For the specimens with long cracks, the situation is not unlike that dealt with in the previous section, except that instead of measuring v versus K, the crack growth rate per cycle dc/dN is measured as a function of ΔK_I, defined as



(*a*) (*b*)

Figure1 (*a*) The stress amplitude versus cycles to failure curve (S/N curve). Inset shows definition of stress amplitude σ_{amp}. *(b)* Curves of log***(dc/dN)*** versus logΔK1. Slope of curve in region II is ***q***, and Δ***K*** is defined in inset.

$$\Delta K_I = \xi(\sigma_{max} - \sigma_{min})\sqrt{\pi c} \quad \text{………………} \ (3)$$

where ζ is a geometric factor of the order of unity.

Typical crack growth behavior of ceramics is represented schematically in Fig. 1b as log $\Delta \boldsymbol{K}_I$ versus log(dc/dN). The resulting curve is sigmoidal and can be divided into three regions, labeled I, II, and III. Below K_{th}, that is, region I, the cracks will not grow with cyclic loading. But just prior to rapid failure, the crack growth is accelerated once more (region III).

In the midrange, or region II, the growth rates are well described by

$$\boxed{\frac{dc}{dN} = B(\Delta K)^q} \quad \text{……………………} \ (4)$$

where B and q are empirically determined constants.

Given the similarity in behavior between fatigue and SCG [compare Figs.2a(Lec.15) and 1b or], one of the major experimental difficulties in carrying out fatigue experiments lies in ascertaining that the degradation in strength observed is truly due to the cyclic nature of the loading and not due to SCG. Even more care must be exercised when the tests are carried out at higher temperatures, since as noted above; SCG is a thermally activated process and hence becomes more important at elevated temperatures.

Micromechanisms of fatigue

At this point, the micromechanics of what is occurring at the crack tip in ceramic materials are not fully understood. The recent results, however, have established that (1) no one micromechanical model can successfully explain all fatigue data in ceramics; (2) fatigue in ceramics appears to be fundamentally different from that of metals, where crack propagation results from dislocation activity at the crack tip; and (3) ceramics that exhibit R curve behavior appear to be the most susceptible to fatigue, indicating that the cyclic nature of the loading somehow diminishes the effect of the crack-tip shielding mechanisms.

Finally, it is interesting to note that the few studies on cyclic fatigue of ceramics at elevated temperatures seem to indicate that at high homologous temperatures (i.e., in the creep regime) cyclic fatigue does not appear to be as damaging as SCG or static fatigue. In the cases where it has been observed, the improved cyclic fatigue behavior has been attributed to bridging of the crack surfaces by grain boundary glassy phases.

Lifetime Predictions during Fatigue

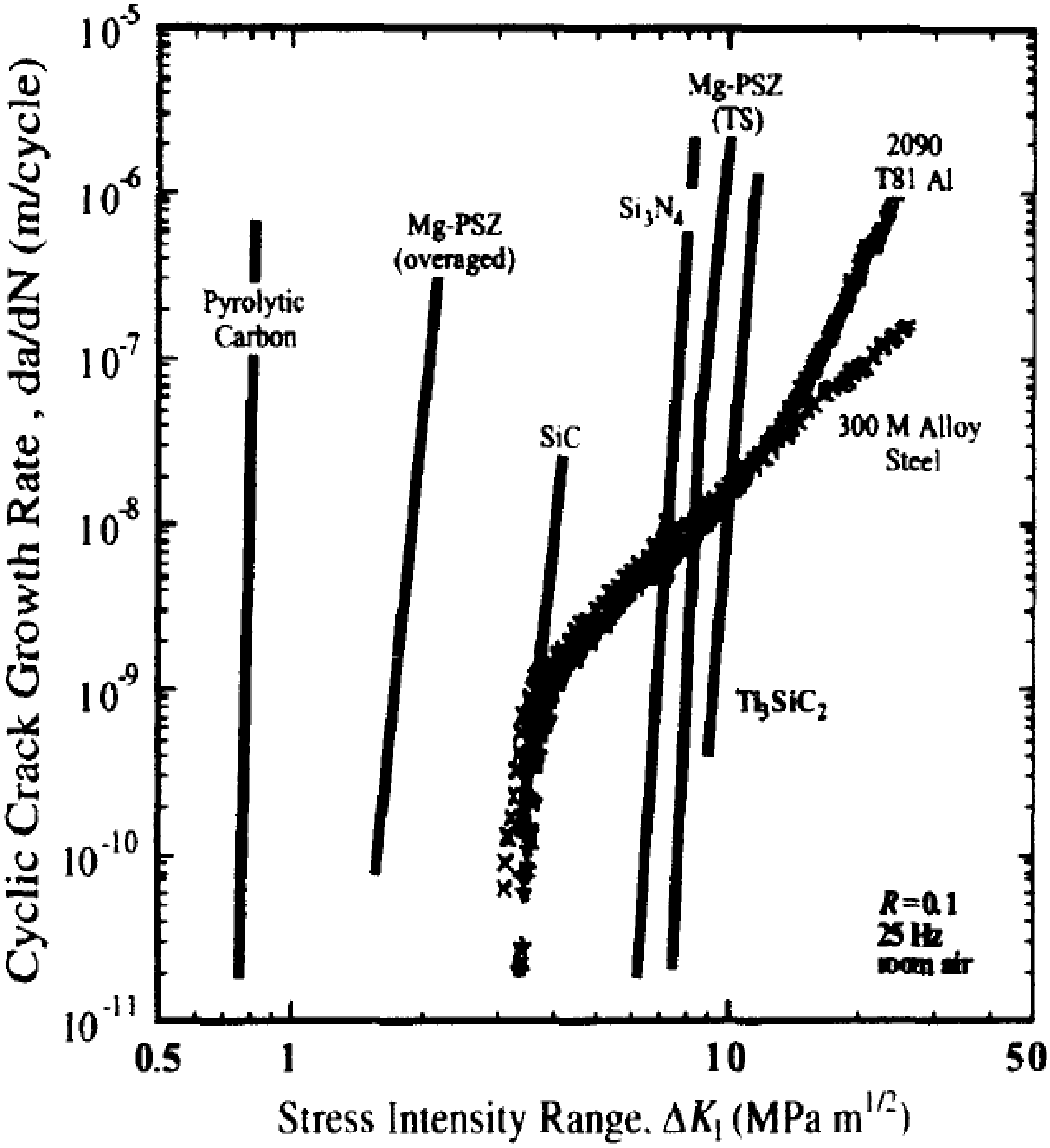
Given the similarities between the shape of the curves in the intermediate region for SCG and fatigue, one can design for a given fatigue lifetime by using the aforementioned methodology. However, given the large values of q, there is little gain in doing so; design based on the threshold fracture toughness ΔK_{th} alone suffices.

The more promising approach at this time appears to be to use S/N curves such as shown in Fig. 1a and simply to design at stresses below which no fatigue damage is expected, i.e., use a fatigue limit approach. The major danger of this approach, however, lies in extrapolating data that were evaluated for simple and usually small parts to large, complex structures where the defect population may be quite different.

Ex.

Estimate the values of B and q for Mg-TZP shown in Fig. below.What are the units of B?
Answer: $B = 1.7 \times 10^{-48}$; $q = 40$

$$V = A\,(K_I/K_{Ic})^n$$


Cyclic Crack Growth Rate , da/dN (m/cycle)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.5
1
10
50
Stress Intensity Range, ΔK_I (MPa m$^{1/2}$)
Pyrolytic Carbon
Mg-PSZ (overaged)
SiC
Si_3N_4
Mg-PSZ (TS)
2090 T81 Al
300 M Alloy Steel
Ti_3SiC_2
R=0.1
25 Hz
room air