3.032 Problem Set 7
Fall 2006
Due: 12/08/06 before the start of lecture

1. Creep can occur via several different mechanisms in amorphous and crystalline materials, each with their own activation energy Q. Typically, there is an Arrhenius behavior to this creep response, with an exponential prefactor that is particular to the material considered and on the operating mechanism.

   (a) You are running two separate creep experiments on polycrystalline Ni, one at 527^oC and the other at 532^oC. You observe that $d\varepsilon/dt$ increases by a factor of 1.5 for the sample tested at the higher temperature. What is the activation energy Q for this creep mechanism?

   (b) What do you think the mechanism at $532oC$ could be, and why? Note that the actual grain size d and stress magnitude need not be stated to figure this out, but you can use deformation mechanism maps to narrow down your options.

   (c) You are running these tests because you would like to develop a new polycrystalline Ni alloy for Boeing aircraft engines. The Ni parts will be under a constant stress of about 1.3 GPa due to centrifugal forces, and a temperature of about 1100^oC. Which creep mechanism are you most concerned about, and how do you propose to modify the polycrystalline Ni alloy to minimize creep rates for this application?

2. One of your colleagues proposes that the advancing crack in the cast copper-and-tin Liberty Bell in Philadelphia, PA could have been halted early on by drilling a small hole just beyond the crack's termination point. Would this be likely to work? Why or why not?

3. Earlier this semester, you learned about the stresses generated in thin-wall pressure vessels and how to calculate the minimum necessary wall thickness to avoid yielding. However, yielding that leads to localized deformation and leaking is far more preferable than the alternate failure mode of rapid crack propagation.

   (a) Assuming Mode I failure, obtain an expression for the maximum crack length in a vessel wall that would allow yielding before crack propagation, assuming a factor of safety of two.

   (b) Select four materials (any class) and rank them by their ability to satisfy the yield-before-break criterion for this application, referencing your data sources. Clearly state any assumptions.

4. A plate of glass is placed under a tensile stress of $60\,\text{MPa}$.

   (a) Determine the maximum surface flaw size that can be accommodated without fracture. Take the specific surface energy of the glass to be $0.3\,\text{J/m}^2$.

   (b) What instruments could you use to visualize flaws of that size, in order to rule in/out the likelihood of such flaws in the as-processed glass?

   (c) Aluminum has the same Young's elastic modulus as glass. Compare the maximum flaw size that could be tolerated in Al without fracture, clearly justifying any assumptions.

5. One of the ways that the yield strength and toughness of alloys like steel are controlled is through a process called tempering, which means heating the material well below the melting temperature to relieve internal stresses via defect annihilation. Unfortunately, strength as measured by σ_y is generally reduced via tempering, whereas toughness as measured by K_{Ic} is increased via tempering.

For example, AISI 4340 steel can go from (σ_y = 1190 MPa; K_{Ic} = 135 MPa $\sqrt{m}$) to (σ_y = 1620 MPa; K_{Ic} = 60 MPa $\sqrt{m}$), varying almost linearly through this range of tempering times/temperatures. It is often important to figure out whether a ductile material component like steel will fail by yielding or by fracture in a particular application such as a vertical member in tension.

   (a) Given that visual inspection of the 4340 steel member can detect all cracks greater than a = 2 mm, determine whether the toughest steel noted above will fail by yielding or fail by fracture. Assume a through-thickness center crack in a semi-infinite body, such that $f = 1$.

   (b) Ideally, the steel should carry the maximum possible load without yielding or fracture. That means it should be processed so that the yield and fracture strengths are the same value. Calculate $\sigma_f(K_{Ic})$ over the range of $50 \leq K_{Ic}$ 150 MPa $\sqrt{m}$. Plot this result on a graph of stress (y-axis) vs. K_{Ic} (x-axis), identifying this ideal yield/fracture strength value as the stress at which $\sigma_y(K_{Ic})$ and $\sigma_f(K_{Ic})$ cross on this graph.

6. Review the paper, "Fatigue behavior of nanocrystalline metals and alloys", Hanlon et al., Int. J. Fat. 27 (2005).

   (a) In your own words, explain why the reduction of grain size d is generally considered a desirable microstructure to increase fracture and fatigue resistance in metals.

   (b) In Section 2.2, the authors detail the experimental conditions for this fatigue life study. Were the fatigued samples ever loaded in compression? How do you know?

   (c) The authors first computed the stress intensity factor K_I according to Eq. 1. Given that they observed later that the range of a/W they accessed was 0.1 to 0.7, what was the range of K_I that they explored, according to Eq. 1?

   (d) What is the J-integral, why did the authors (and anyone else) use it to consider this material's fracture behavior, and what was the range of the J-integral they explored, according to Eqs. 1 - 2?

   (e) In Section 3, the authors relate their results. Why do you think the ductility of the nanocrystalline, ultrafine crystalline, and microcrystalline Ni ranked the way they did?

   (f) What is the fatigue limit (i.e., stress amplitude in [Pa]) of nc, ufc, and mc Ni, according to Hanlon et al., Scripta Mater. (2003) as reproduced in Fig. 4?

   (g) What is the fatigue crack growth threshold or threshold stress intensity factor $_o$ for nc Ni at the various load ratios considered, according to Fig. 5?

   (h) Assuming that the cyclic crack growth characteristics of nc and ufc Ni are well characterized by the Paris law, determine the values of C and m for both materials from

the data in Figs. 5a-c. From this analysis, state whether you find the fatigue fracture lifetime to be a stronger function of microstructure or of loading conditions, and why you think this to be the case.

(i) Briefly explain the mechanisms you understand to be responsible (either from the paper or your own knowledge via 3.032 and other sources) for the chief conclusion of the authors: Grain size reduction correlated with decreased subcritical fatigue fracture in nc Ni, but also to an increased total fatigue life.

7. Select one topic that has been covered this semester in 3.032 (other than visco/rubber elasticity) and contribute to the corresponding Wikipedia article (or create a new article if none exists). This is a good opportunity to get up to speed in any areas in which you lack confidence.

- An ideal contribution will be several paragraphs of correct and useful information, possibly including equations or figures.

- Make sure to reference your sources correctly.

- It will make grading easier if you make a single update (proofread your work first) rather than multiple updates. Please print out your contribution *or* indicate the article URL and your user name in your pset.

Congratulations on completion of your last graded pset for 3.032!