Examination Paper: *Mechanisms of Deformation and Transport in Rocks*

Part II (Spiers) 16-04-2014 13.30 -16.30 hours Room: Unnik 211

Note:

- The duration of this exam is 3 hours.
- Answer any 4 of the 7 questions given.
- All questions count with equal weight to the final grade.
- Allow about 45 minutes per question.
- Answers may be given in English or Dutch.
- Make sure you identify all mathematical symbols used in answering the questions (marks will be deducted for unidentified symbols).
- Use SI units unless otherwise specified.

Good luck all !!!

Question 1

a) Taking into account the symmetry of the elastic stiffness matrix (C_{rs}), the non-zero components of this matrix for an ***olivine*** crystal (orthorhombic) are specified as follows:-

$$\left.\begin{matrix} C_{11} = 3.00 & C_{22} = 1.80 & C_{33} = 2.10 \\ C_{23} = 0.69 & C_{31} = 0.61 & C_{12} = 0.60 \\ C_{44} = 0.58 & C_{55} = 0.71 & C_{66} = 0.70 \end{matrix}\right\} \times 10^{11}\ \text{Pa}$$

referred to the orthorhombic crystal axes x_1, x_2, x_3. ***Write out the matrix C_{rs} in full.***

b) An olivine single crystal A is deformed at constant temperature to an elastic strain given by the tensor

$$\varepsilon_{ij} = \begin{bmatrix} 1 & 2 & 0 \\ 2 & -1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \times 10^{-4} \quad \text{(referred to its crystal axes } x_1, x_2, x_3\text{)}$$

Use C_{rs} to calculate the resulting state of stress, writing your answer in both matrix and tensor notations and stating the units clearly.

c) Calculate the change in the Helmholtz free energy of the crystal relative to the undeformed state.

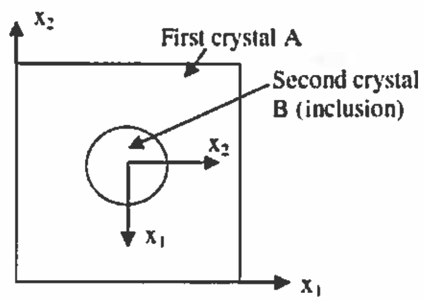
d) Suppose that the above crystal (A) contains a second olivine crystal (B) as an inclusion, and that the crystal axes of this included crystal are orientated as shown in the figure on the right. If the strain given under question (b) is applied uniformly throughout both crystals (homogeneous strain field), what is

-the state of strain in B, specified with respect to its own crystal axes?

-the state of stress in B, specified with respect to its own axes?

-the change in Helmholtz free energy of B relative to the undeformed state?

-the difference in Helmholtz free energy between A and B?



e) If grain boundary migration is possible, in the above configuration, will B grow or shrink?

Question 2

a) Explain what vacancies are and write down an equation for the equilibrium concentration of thermally produced vacancies in a pure elemental crystal maintained at a temperature T (K) and hydrostatic pressure P. Define all symbols appearing !!

b) Explain the statistical meaning of your answer to (a), with reference to the Boltzmann distribution law.

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c) Derive an equation to show how the equilibrium concentration of vacancies is modified at a grain boundary transmitting a normal stress σ_n (superimposed on the hydrostatic component P), and hence explain the theoretical basis (driving force) for solid state diffusion creep.

d) Explain the possible pathways for vacancy and atomic diffusion during deformation by solid state diffusion creep, and identify the physically possible rate controlling steps using an electrical circuit analogue diagram. Which of these rate limiting steps do you expect to be most important in a typical crystalline solid?

e) Write down the theoretical rate equations for the two best known processes of solid state diffusion creep. Name the two processes. Under what grain size and temperature conditions will the one dominate over the other, and why? Will these mechanisms become more or less important with increasing pressure (e.g. with depth in the mantle)?

Question 3

a) Explain what is meant by the term "superplasticity" (i.e. structural superplasticity).

b) What are the principal rheological and microstructural characteristics exhibited by crystalline materials that show superplastic deformation behaviour?

c) Explain what microphysical mechanisms give rise to superplastic flow in metals, ceramics and rocks.

d) Why do materials deforming by glide or cross-slip controlled creep not show superplastic behaviour?

e) Mylonitic shear zone rocks often show evidence for the operation of the processes responsible for superplastic flow. Explain **three** ways in which such behaviour can become localized in shear zones and outline the implications for the strength of major shear zones compared to surrounding host rock.

Question 4

a) Draw a sketch of a planar segment of grain boundary penetrated by a solution phase in island-channel or thin film form. If the segment transmits a normal stress σ_n, write down an approximate expression for the average chemical potential of the solid within the grain boundary segment. Identify all of the symbols used and state their units.

b) Consider a granular pack of quartz grains (diameter d) in which the pores are filled with a saturated solution phase. If the solid skeleton is instantaneously subjected to an externally applied hydrostatic stress P and the liquid to a lower hydrostatic pressure p, describe how the system will respond?

N.B. Assume i) that interfacial energy driving forces are negligible, ii) that grain contacts are penetrated by fluid in island-channel form, and iii) that deformation within the grains is elastic.

c) Explain what processes would control the rate at which the response of the system would occur for a fixed value of applied stress and fluid pressure.

d) List the steps you would take to construct a model of the system response (do not derive models)

e) What is the application of such models in the Earth sciences?

Question 5

a) Explain, in terms of dislocation dynamics, what is meant by the terms "work hardening" and "recovery".

b) Go on to describe how these processes can lead to steady-state creep in rocks at elevated temperatures.

c) Develop a rate model for deformation by high-temperature, cross-slip controlled dislocation creep where the obstacles to dislocation glide are attractive junctions (dipoles) between screw dislocations of opposite sign.

d) Use your resulting equation to sketch a graph illustrating qualitatively how $\ln(\dot{\varepsilon})$ depends on $\ln(\sigma)$ at constant temperature (in other words show the shape of the curve). Then, add to this graph a line showing qualitatively how $\ln(\dot{\varepsilon})$ depends on $\ln(\sigma)$ for high temperature, climb controlled creep. **NOTE: draw both lines/curves passing through the origin of your graph.**

e) Using your graph, explain what the main differences are between cross-slip and climb-controlled creep, in terms of how sensitive the strain rate is to applied stress (in other words, explain which is the more sensitive to changes in stress). From your graph, and assuming that the two mechanisms act as parallel processes, which mechanism do you expect to be fastest (dominant) at high stress and which at low stress?

Question 6

a) Explain what is meant by dynamic recrystallization and outline the main mechanisms of microstructural change involved in this process.

b) How is the dynamically recrystallized grain size that develops during steady state dislocation-dominated flow typically reajted to flow stress and temperature?

c) Recent work has shown that dynamic recrystallization reorganises the grain size of a material to lie in the boundary between dislocation creep (grain size insensitive) and diffusion creep (grain size sensitive). Use this concept to obtain an alternative relationship between steady state flow stress and recrystallized grain size. Hint: Assume that dislocation creep is climb controlled with $3 \leq n \leq 5$ and diffusion creep is dominated by grain boundary diffusion.

d) Is the result you obtain similar to or different from that you obtained in practical classes using the Avrami equation? Why do you think the result is similar or different?

e) Explain under what circumstances dynamic recrystallization can lead to shear zone localization and whether or not recrystallized grain size versus stress relations can then be applied to estimate paleostresses.

Question 7

a) Measured values of the tensile fracture strength (T_o) of brittle materials are usually much lower than the theoretical ("bond strength) value σ_T. Why is this?

b) Consider a flat "elliptical" crack (length 2a) within an infinite plate of elastic material (Young's Modulus E) and suppose that this plate (which is of unit thickness) is subjected to a remote uniaxial tensile stress (σ) oriented normal to the crack surface. The applied stress will give rise to a stored elastic energy U_e within the plate. Given that the rate of change of U_e with respect to crack length can be written

$$\frac{d\,U_e}{da} = \frac{-2\pi a \sigma^2}{E}$$

derive the Griffith failure criterion for uniaxial tensile loading. **State any assumptions made.**

c) Go on to explain what is meant by the terms "stress intensity factor" and "critical stress intensity factor", ideintifying all terms appearing.

d) Re-write the Griffith criterion in terms of stress intensity factor and critical stress intensity factor.

e) A sample of low porosity but still permeable quartzite is loaded uniaxially, at room temperature and under dry conditions, to 80% of its brittle compressive failure strength. An initial instantaneous shortening of 0.3% occurs when the load is applied. The pores of the rock are then flooded with water at atmospheric pressure and the sample immediately fails. Explain why!