

National Exams May 2017

10-MET-A5: Mechanical Behaviour and Fracture of Materials

3 hours duration

Notes:

1. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer paper, a clear statement of any assumptions made.
2. This is a CLOSED BOOK EXAM.
Any non-communicating calculator is permitted.
3. FIVE (5) questions constitute a complete exam paper.
The first five questions as they appear in the answer book will be marked.
4. Each question is of equal value.
5. Some questions require an answer in essay format. Clarity and organization of the answer are important.

Question 1: (20 Marks)

- (a) A steel component with $\sigma_{UTS} = 800$ MPa and $K_{Ic} = 20$ MPa \sqrt{m} is known to contain a centrally positioned, through-thickness crack of length 1.4 mm (assume the component configuration correction factor for stress intensity is unity. This alloy is being considered for use in a cyclic loading application for which the design stresses vary from 0 to 410 MPa. Would you recommend using this alloy in this application? *(10 marks)*
- (b) Consider a metal component used for a skeletal implant that failed prematurely following exposure to cyclic tensile-compressive loading. The component should have been designed to achieve an infinite fatigue life (i.e. 1×10^7 cycles). It is known that the maximum initial surface crack length was 0.01 in. and the maximum tensile stress was 15,000 psi. Compute the largest, tolerable surface crack size to achieve an infinite fatigue life. Assume the component configuration correction factor for stress intensity is independent of crack length and has a value of 1.75, and that n and A have values of 2.5 and 1.5×10^{-18} , respectively, for $\Delta\sigma$ and a in units of psi and in., respectively. *(10 marks)*

Question 2: (20 marks)

- (a) Briefly describe the mechanical test procedures for creep and fatigue testing of a material of your choice and schematically illustrate how the mechanical property data is represented (i.e. compare a typical “creep curve” with a typical “fatigue curve”). *(10 marks)*
- (b) Tough" materials are usually best suited for mechanical design. Define "toughness" for the case of: (i) elastic deformation, (ii) plastic deformation and (iii) fast fracture. *(10 marks)*

Question 3: (20 marks)

- (a) A relatively large sheet of steel with a fracture toughness, $K_{Ic} = 25 \text{ MPa} \sqrt{\text{m}}$ is to be exposed to a cyclic tensile stress of 100 MPa. Prior to testing it has been determined that the component contains surface cracks up to as large as $a = 2.0 \text{ mm}$ in length. If the cyclic crack growth rate is under steady state conditions where: $\frac{da}{dN} = A (\Delta K)^n$, $A = 1 \times 10^{-12} \text{ MPa}^{-3} \text{m}^{-1/2}$ and $n = 3$, estimate the fatigue life (ie. the number of cycles to failure, N_f). **(10 marks)**
- (b) The nominal stress-strain curve for a tough engineering material, as obtained from a tensile test for example, defines the stresses for the onset of general yielding (σ_y) and final fracture (σ_f). However it is known that materials can catastrophically fail at stresses, $\sigma < \sigma_y$ such that the stress-strain curve becomes a poor measure of the integrity of a material. Describe in sufficient detail two different conditions and the associated mechanisms whereby a tough material can fail at stresses $\sigma < \sigma_y$. **(10 marks)**

Question 4: (20 marks)

- (a) Single crystals of pure metals are not very useful for most mechanical design applications. Based on the above statement, describe in sufficient detail two methods by which a specific metal of your choice can be strengthened for improved mechanical strength. *(10 marks)*
- (b) Explain why nickel-based superalloy turbine blades for jet engine applications are produced in single crystalline form by directional solidification. (N.B. Your answer must consider microstructural aspects of the relevant structure-property relationship). *(10 marks)*

Question 5: (20 marks)

- (a) Steel plate is to be used in the construction of a marine vessel. The steel has a fracture toughness (K_{IC}) of $53 \text{ MN m}^{-3/2}$ and a yield strength (σ_y) of 950 MN m^{-2} . It is possible that surface cracks may be produced during construction and the *smallest* surface crack depth that can be detected by ultrasonic inspection methods is $a = 1.0 \text{ mm}$. Assuming that the plate contains cracks at the limit of detection, determine whether the plate will undergo general yield or will fail by fast fracture before general yielding occurs. **(10 marks)**
- (b) Why are large structures (e.g. ships, bridges and oil rigs) made of steel much more likely to fail in cold winter environments rather than in warm summer climates? **(5 marks)**
- (c) Briefly explain why HCP metals are typically more brittle than FCC and BCC metals. **(5 marks)**

Question 6: (20 marks)

- (a) Using a single set of axes compare the *nominal* stress-strain curves for the following two engineering materials: (i) a tough polycrystalline metallic alloy and (ii) a semicrystalline polymer. Using sketches where appropriate, describe the changes in microstructure for each material type during stressing from the elastic limit to the ultimate tensile stress. **(10 marks)**
- (b) The development of composite structures has led to dramatic improvements in toughness, stiffness and strength of polymer-based materials. Briefly explain why a ceramic fibre-reinforced plastic (e.g. CFRP) leads to greater (i) stiffness, (ii) strength relative to the polymer matrix and greater fracture toughness relative to both the ceramic and polymer phases. **(10 marks)**

Question 7: (20 marks)

- (a) Consider a nominal stress-strain curve for a ductile material loaded in tension. At the point of plastic instability the work hardening capability of the material is balanced by the applied stress. The work hardening rate of materials is usually described by a power law of the form: $\sigma = K\varepsilon^n$ where σ and ε are the true stress and true strain respectively, K is a constant and n is the work hardening exponent. Show that plastic instability (i.e. necking) occurs when $\varepsilon = n$. (10 marks)
- (b) A 1.5 mm thick, 80 mm wide sheet of magnesium that is originally 5 m long is to be stretched to a final length of 6.2 m. What should be the length of the sheet before the applied stress is released? ($E = 65 \text{ GNm}^{-2}$ and $\sigma_y = 200 \text{ MNm}^{-2}$). (10 marks)

Question 8: (20 marks)

- (a) The nominal stress-strain curve for a metal, as obtained from a tensile test for example, defines the stresses for the onset of yield (σ_y) and final fracture (σ_f). However it is known that metals can deform plastically at stresses, $\sigma < \sigma_y$ by creep and fracture at stresses $\sigma < \sigma_f$ by fatigue. Under what conditions can metals be made to: (i) creep and (ii) fatigue? *(5 marks)*
- (b) Using a microstructural description discuss in sufficient detail one mechanism by which creep deformation can occur at stresses $\sigma < \sigma_y$. *(8 marks)*
- (c) Why are materials whose yield stresses are highly strain-rate dependent more susceptible to brittle fracture than those materials whose yield stresses do not exhibit marked strain-rate dependence? *(7 marks)*