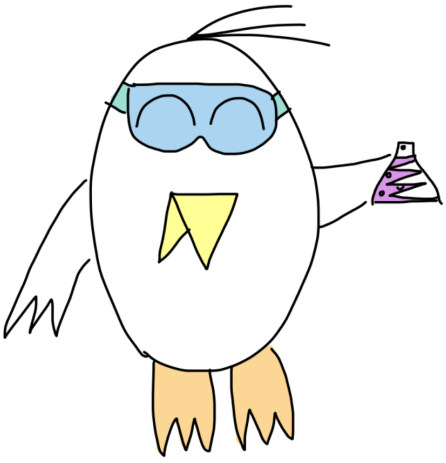
'Iolani Science Olympiad Invitational 2024

Division C

MATERIALS SCIENCE TEST



Team Name _____

Team Number _____

Honolulu
2024

1 Short answer

1. (1 point) Identify the Bravais lattice corresponding to the dihedral point group with a 3-fold rotation axis, 3 twofold axes perpendicular to that axis, and 3 vertical mirror planes which pass between twofold axes.

2. (1 point) How many Bravais lattices are there in 4 dimensions?

3. (2 points) A metal has a face-centered cubic structure with a lattice parameter of 4.00 Angstroms. The atomic mass is 58.7 g/mol. Calculate the density for this metal. Give your answer in SI units.

4. (4 points) Consider a monochromatic x-ray beam with a wavelength $\lambda = 0.154$ nm (characteristic of Cu K-alpha radiation) incident on a crystalline material known to have a cubic structure with a lattice constant 0.4 nm. The beam is directed at a set of crystallographic planes indexed by their Miller indices (h, k, l).

(a) Determine the first-order Bragg angle for the $(1, 1, 1)$ planes. Provide your answer in degrees.

(b) For the same crystal, the intensity of the reflected x-ray is measured to be maximum at $\theta = 25.6°$. Calculate the Miller indices of the planes responsible for this diffraction, considering only diffracted x-rays of the first order.

5. (2 points) Niobium has the body-centered cubic crystal structure. Given that the density of Nb is 8,570 kg/m^3, and the atomic weight is 92.91 g/mole, what is the atomic radius (in pm) and the lattice parameter of Nb?

6. (2 points) Titanium diboride, important ceramic material, has a composition of two B atoms for every Ti atom. What weights of Ti and B must be mixed together to make a 100g ingot of TiB_2? The atomic weights are Ti=47.88, B=10.81, and the densities are Ti=4.51 g/cc and B=2.34 g/cc.

7. (1 point) In a typical X-ray crystallography experiment, X-rays of wavelength 0.71 Angstroms are generated by bombarding molybdenum metal with an energetic beam of electrons. Why are these X-rays more effectively diffracted by crystals than is visible light?

8. (1 point) What is the closest-packed plane in BCC? Give your answer in Miller indices.

9. (2 points) Draw a plane with Miller indices (-2,-1,1).

10. (3 points) You are given a material and told that it is elastically isotropic and exhibits a yield strength of 950 MPa. The material experiences a stress state of

$$\sigma_{ij} = \begin{bmatrix} 0 & 0 & 300 \\ 0 & -400 & 0 \\ 300 & 0 & -800 \end{bmatrix} \text{ MPa}$$

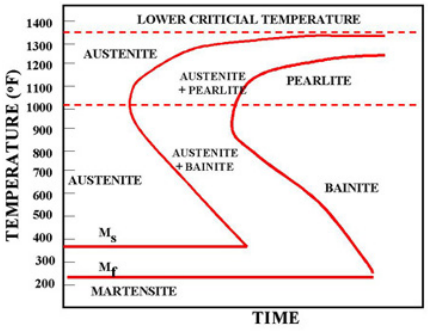
According to the von Mises and Tresca criteria respectively, does the material yield? Justify your answer.

11. (1 point) A borosilicate glass plate has a thermal expansion coefficient of $3.3 \times 10^{-6}\text{K}^{-1}$, Young's modulus of 64 GPa, and fracture strength of 50 MPa. calculate the maximum temperature difference the glass can withstand without breaking.

12. (2 points) Calculate the dielectric constant of a glass material with a polarizability of $\alpha = 1.0 \times 10^{-40}$ F$\cdot$m^2 and a number density of dipoles $N = 2.5 \times 10^{28}$ m^{-3}.

13. (1 point) What is the molar heat-capacity of a solid crystalline substance as predicted by the Dulong-Petit law?

14. (2 points) Given the TTT diagram below, percentage the fraction of pearlite transformed in a eutectoid steel isothermally held at 700 C for 5 seconds. Assume an Avrami exponent $n = 2$ and a rate constant $k = 0.05\text{s}^{-1}$.

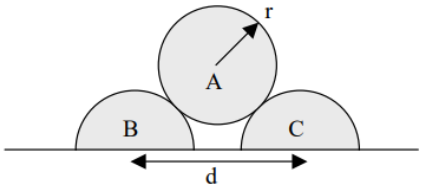


15. (2 points) A ceramic material is studied as a potential high-temperature superconductor. Within the material, electrons are modeled as confined to a 2D potential well (representing the crystal plane) with an effective mass $m = 0.2m_e$, where m_e is the mass of the free electron. The dimensions of the potential well are $L_x = 0.5$ nm and $L_y = 0.3$ nm. Determine the wavelength of a photon required to excite the electron from the ground state to the first excited state, in nanometers.

16. (2 points) Consider a single crystal of BCC iron oriented such that a tensile stress is applied along a [010] direction. If slip occurs on a (110) plane and in a $[\bar{1}11]$ direction, and the critical resolved shear stress is 30 MPa, calculate the magnitude of applied tensile stress necessary to initiate yielding.

17. (2 points) Silicon and Gallium Arsenide crystals can be described by an FCC lattice with two atoms per unit cell. The primitive vectors of the FCC lattice expressed in the Cartesian basis are given by $\vec{a}_1 = \frac{a}{2}(0,1,1)$, $\vec{a}_2 = \frac{a}{2}(1,0,1)$, $\vec{a}_3 = \frac{a}{2}(0,1,1)$ with a the lattice parameter. The basis vectors that describe the positions of atoms inside the unit cell are given by $\vec{\tau}_1 = \frac{a}{4}(1,1,1)$ and $\vec{\tau}_2 = -\frac{a}{4}(1,1,1)$. Find the reciprocal space primitive vectors.

18. (3 points) A circular cylinder A rests on top of two half-circular cylinders B and C, all having the same radius r. The weight of A is W, and that of B and C is W/2 each. Assume that the coefficient of friction between the flat surfaces of the half-cylinders and the horizontal table top is μ_s. Determine the maximum distance d between the centers of the half cylinders to maintain equilibrium.



19. (3 points) You're building a small-scale wooden electrical vehicle, and you're in a hurry to get it done quickly before impound (you woke up at 4AM with nothing but a motor and an Arduino). Part of the model needs to be a structural member that has a length L and a square cross-section with side length L/10, and this structural member will be loaded in tension. At the last minute, you realize that you don't have any pieces of wood that are long enough; your longest pieces have a length of 0.8L. You do, however, have a bottle of glue that you can use to glue two pieces together to get the total length that you need. Your glue can withstand 1MPa of shear stress and 3MPa of normal stress. You also have a saw that you can use to cut the ends of the pieces of wood at any angle that you like prior to gluing. At what angle θ should you cut the wood faces if you want the resulting beam to be able to withstand the largest possible tensile load? (You can only cut a straight cut).

20. (4 points) Consider a cylindrical tank of radius 1 m, length 2 m, and wall thickness 3 cm made of an isotropic linear elastic material with modulus 100 GPa and Poisson's ratio 0.3. The tank fits without stress between a rigid wall and a rigid plate when there is no pressure in the tank. A spring with spring constant 1 giganewton per meter fits exactly between the rigid plate and a second rigid wall. The plate can only move in the horizontal direction. The internal pressure in the tank is brought to a value 500 MPa. Obtain the resulting displacement of the plate and the change in wall thickness.

2 Multiple choice

Each problem is worth 2 points.

1. During the sol-gel process for fabricating ceramic or glass materials, which of the following factors most significantly impacts the final pore structure of the material?

(a) Type of precursor used (e.g., alkoxides vs. nitrates)

(b) The water-to-alkoxide molar ratio during hydrolysis

(c) The curing temperature used before sintering

(d) The duration of the aging process of the gel

2. In tape casting, which of the following additives is primarily responsible for controlling the viscosity of the ceramic slurry?

(a) Binder

(b) Plasticizer

(c) Dispersant

(d) Solvent

3. Which of the following techniques is NOT typically used to reduce the sintering temperature of ceramic materials?

(a) Addition of a fluxing agent

(b) Spark plasma sintering

(c) Increasing the green density

(d) Using a higher cooling rate after firing

4. In the Czochralski process for producing single-crystal glass, what is the primary role of the rotation of the seed crystal?

(a) Prevent thermal gradients from cracking the crystal

(b) Promote uniform crystal growth by reducing solute boundary layers

(c) Control the incorporation of dopants into the crystal

(d) Align the crystal structure with the pulling direction

5. During the hot isostatic pressing (HIP) of ceramics, which factor is most critical for eliminating closed porosity without causing abnormal grain growth?

(a) The applied gas pressure

(b) The sintering atmosphere composition

(c) The heating rate during the process

(d) The temperature-holding time at peak pressure

6. In slip casting, which of the following defects is most likely caused by improper deflocculation of the slurry?

(a) Warping during drying

(b) Weak mechanical strength after sintering

(c) Non-uniform thickness of the green body

(d) Excessive cracking during the drying stage

7. Which phenomenon is most responsible for the increased mechanical strength observed in tempered glass?

(a) Decrease in residual thermal stresses due to quenching

(b) Compressive stresses introduced at the surface during cooling

(c) A transition from amorphous to partially crystalline structure

(d) Increased density of covalent bonding in the silica network

8. In the additive manufacturing (3D printing) of ceramics, which of the following methods typically achieves the highest density in the final product after post-processing?

(a) Binder jetting

(b) Vat photopolymerization

(c) Material extrusion

(d) Laser sintering

8. Which of the following steps in the fabrication of zirconia-toughened ceramics most directly contributes to the transformation toughening mechanism?

(a) Sintering at temperatures above the monoclinic phase stability range

(b) Rapid cooling to retain the tetragonal phase in the final product

(c) Inclusion of yttria as a stabilizer during powder preparation

(d) Homogenizing the initial powder blend to eliminate impurities

10. In the float glass process, what is the primary purpose of using molten tin in the fabrication of flat glass sheets?

(a) To enhance the thermal conductivity of the glass during annealing

(b) To achieve a perfectly flat surface without grinding or polishing

(c) To reduce the melting temperature of the silica precursor

(d) To provide a nucleation site for glass crystallization