Surname, given names:
Student Number:

Multiple Choice – True/False Answer Sheet

Detach this sheet from the answer book to make your task easier but **ensure that your name and student ID number are on this page as well as on your exam paper.**

1. For questions (1-45), **fill in**, or put a distinct **X** in the box containing the letter of the "**best**" answer to that question, E.g. If you want answer (b) fill in the box containing (b) as indicated.

1	a	b	c	d	e

2. The numbers refer to the question numbers on the exam paper.
3. Fill in only one box per question. A line with two or more responses will be treated as blank.

Q					
1	a	b	c	d	e
2	a	b	c	d	e
3	a	b	c	d	e
4	a	b	c	d	e
5	a	b	c	d	e
6	a	b	c	d	e
7	a	b	c	d	e
8	a	b	c	d	e
9	a	b	c	d	e
10	a	b	c	d	e
11	a	b	c	d	e
12	a	b	c	d	e
13	a	b	c	d	e
14	a	b	c	d	e
15	a	b	c	d	e
16	a	b	c	d	e
17	a	b	c	d	e
18	a	b	c	d	e
19	a	b	c	d	e
20	a	b	c	d	e
21	a	b	c	d	e
22	a	b	c	d	e
23	a	b	c	d	e
24	a	b	c	d	e
25	a	b	c	d	e

Q		
26	T	F
27	T	F
28	T	F
29	T	F
30	T	F
31	T	F
32	T	F
33	T	F
34	T	F
35	T	F
36	T	F
37	T	F
38	T	F
39	T	F
40	T	F
41	T	F
42	T	F
43	T	F
44	T	F
45	T	F

Concordia University
Engineering and Computer Science

Name:______________________________________
Surname, given names

I.D.: _______________________

Department of Mechanical & Industrial Engineering

COURSE		**NUMBER**	**SECTION**
PROPERTIES AND FAILURE OF MATERIALS		MECH 321/4	X & T
EXAMINATION	**DATE**	**TIME**	**# OF PAGES**
FINAL	April 18, 2018	2 – 5pm	15

PROFESSORS
Dr Martin Pugh (T)
Dr Mamoun Medraj (X)

MATERIALS ALLOWED	☐	**NO**	■	**YES (SPECIFY)**	**English-French Dictionary**
CALCULATORS ALLOWED	☐	**NO**	■	**YES**	**ENCS Approved**

SPECIAL INSTRUCTIONS:

1. **Write your name and ID number in the specified space above AND on the multiple choice answer sheet.**
2. **Attempt all questions.**
3. **For the multiple choice and True/False questions in Part A select the <u>best</u> answer from those given, and shade in the box with the appropriate letter for that question number on the special answer sheet provided.**
4. **Answer the questions in Part B in this Booklet in the space provided.**
5. **Questions 1-25 are worth 2 marks each (50 marks subtotal) and 26 to 45 are worth 1 mark each (20 marks subtotal). The values of Q46 - 47 are indicated in the left margin (34 marks subtotal).**
6. **The total number of marks for the exam is 104.**
7. **An equation sheet is attached at the end of the paper.**
8. **The multiple choice answer sheet and the equation sheet may be detached CAREFULLY from the exam book.**

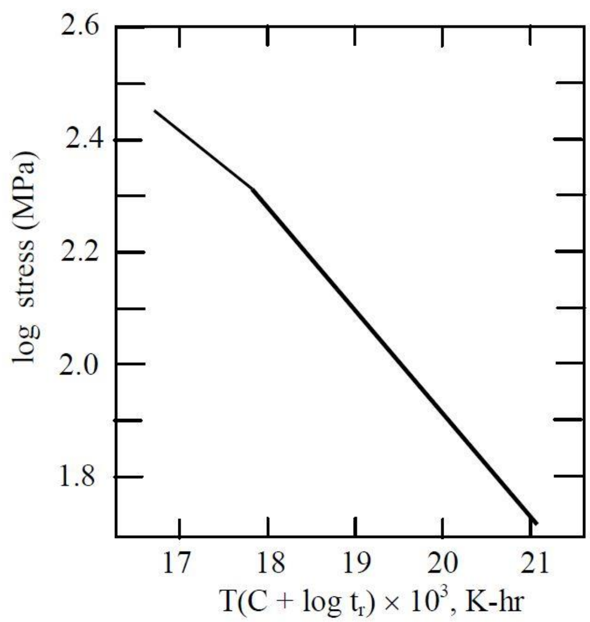
PART A: Questions 1-25: Multiple-choice questions *[2 marks each]*

1. A tensile specimen machined from a jet engine alloy is subjected to a constant load at a temperature of 1000 ^oC. The load is such that the initial tensile stress in the sample is less than the room temperature yield strength. This specimen will:

a) elongate slowly after the load is applied and will eventually fail by the intermittent propagation of a crack through the specimen resulting in a fracture surface which contains lines or beach marks pointing to the origin of the crack.
b) elongate almost instantaneously, and will then continue to elongate for an extended period of time until failure which will occur at a stress level less than the room temperature tensile strength.
c) elongate almost instantaneously, and because the stress is constant the specimen will retain this constant elongation which can be predicted from the room temperature stress/strain curve for the material.
d) not encounter any elongation because jet engine alloys are very creep resistant.
e) elongate slowly from its initial length for an extended period of time until failure which will occur at a stress level less than the room temperature tensile strength.

2. A Larson-Miller plot for some hypothetical metal alloy is shown in the following figure. It is known that at a stress level of 126 MPa and at 950 K, rupture occurs at 1000 hr. On this basis, calculate the rupture life time at a stress level of 200 MPa and 800 K.

a) 100 years
b) 27 years
c) 5 months
d) 17 weeks
e) Cannot solve because the value of C is missing



3. A ceramic part fails in tension at 50 MPa. Microscopy reveals an external flaw (0.095 mm long) in the failed part that caused the failure. Calculate the radius of curvature of the flaw, if the resulting stress concentration factor is 11.

a) 1×10^{-6}m
b) 2.1×10^{-6} m
c) 3.14×10^{-6} m
d) 0.95×10^{-6} m
e) 6 mm

4. Wood has a Young's modulus of 1×10^{10} Nm^{-2} when tested parallel to the grain and a value of 7×10^8 Nm^{-2} perpendicular to the grain. A wooden block loaded in compression will therefore:

a) compress more if the loading is along the grain than if it is perpendicular to the grain.
b) compress less if the loading is along the grain than if it is perpendicular to the grain.
c) compress the same amount whether loaded parallel to or perpendicular to the grain.
d) most likely fracture since wood is almost always loaded in tension.
e) compress the same amount if loaded parallel or perpendicular to the grain but failure will occur at a lower stress if the load is perpendicular to the grain.

5. An aluminum alloy sample is being prepared for measurement of plane strain fracture toughness, K_{1c}. The alloy has a yield strength of 525 MPa, a ductility of 22 % Elongation and a Young's Modulus of 69 GPa . What is the minimum width of the fracture toughness sample?

   a) 5 mm
   b) 7.61 mm
   c) 10 mm
   d) ASTM standard thickness (4 x specimen depth)
   e) not enough information is given.

6. A heat treatment process used to relieve stresses and refine grains is called:

   a) annealing
   b) polarisation
   c) austempering
   d) quenching
   e) aging

7. An apprentice is asked to heat-treat a 1% C steel sword blade to make it strong, hard and tough. Which of the following instructions would you give her/him? (*Recall that the Fe-Fe_3C eutectoid temperature is 727°C*)

   a) heat to 950°C and slowly cool to room temperature
   b) heat to 950°C, quench, and temper between 200°C – 300°C
   c) heat to 600°C, quench and temper at 200°C
   d) heat to 727°C and quench
   e) heat to 727°C and slowly cool

8. If a unidirectionally reinforced carbon fibre – epoxy composite has an Elastic modulus in the fibre direction of 177 GPa, what will be the elastic modulus perpendicular to the fibre direction? (E_{carbon} = 290 GPa, E_{epoxy} = 3.1 GPa).

   a) 7.74 GPa
   b) 2.52 GPa
   c) 5.08 GPa
   d) 177 GPa
   e) 3.1 GPa

9. On a particularly heavy traffic day, enough traffic stops on a bridge to increase the tensile stress in each cable to 550 MPa (which is above the yield strength of the cable). If the total strain in the cable under load is 0.006, what would be the permanent strain in the cable if it was fully unloaded? The Young's modulus of the cable is 200GPa.

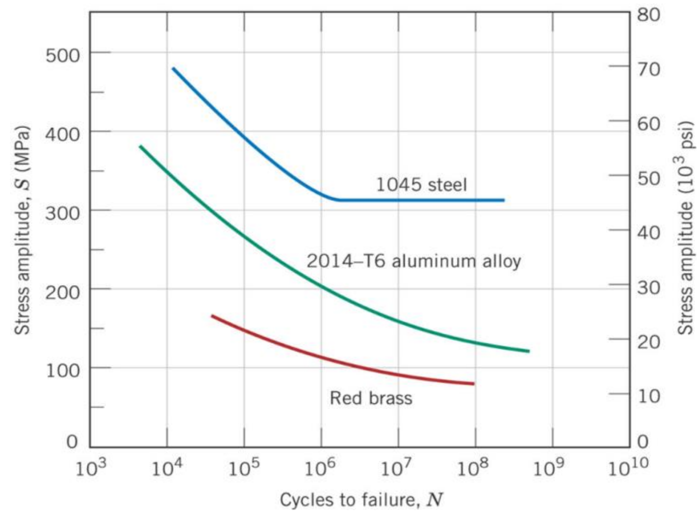
   a) 0
   b) 0.0016
   c) 0.0027
   d) 0.0033
   e) 0.006

10. When selecting a material for a biomedical application, e.g artificial hip, which of the following is the least serious consideration?

    a) compatibility with body fluids,
    b) corrosion resistance,
    c) strength and stiffness,
    d) fatigue resistance,
    e) thermal expansion mismatch.

11. A cylindrical 1045 steel bar is subjected to repeated compression-tension stress cycling along its axis with a mean stress of zero. If the load amplitude is 22,000 N, compute the minimum allowable bar diameter to ensure that fatigue failure will not occur. Assume a factor of safety of 2.0.

    a) 4.6 mm
    b) 9.8 mm
    c) 13.4 mm
    d) 18.3 mm
    e) 25.0 mm

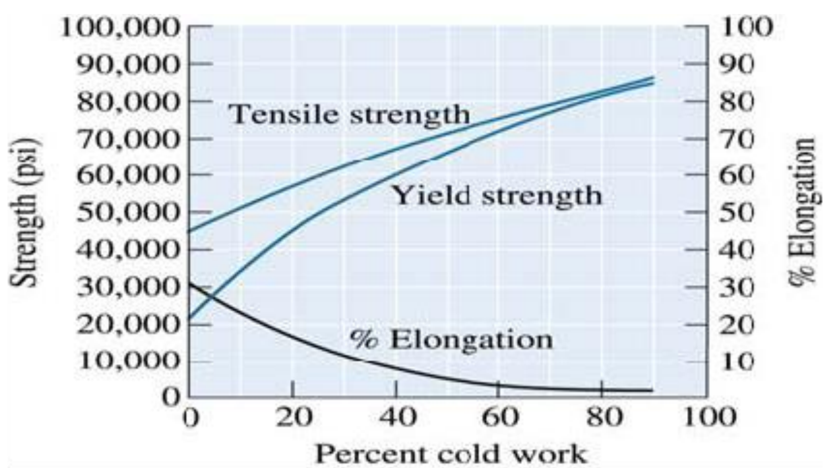


12. Shot peening:

    a) increases fatigue resistance mainly by increasing the radius of fine notches
    b) decreases fatigue resistance mainly by increasing the surface roughness
    c) increases fatigue resistance mainly by inducing surface residual tension stresses.
    d) increases fatigue resistance mainly by inducing surface residual compression stresses.
    e) decreases fatigue resistance mainly by inducing surface residual compression stresses.

13. A 1 cm thick copper plate is reduced in thickness by cold working to 0.50 cm, and then further reduced to 0.30 cm. Determine the total percent cold work and the tensile strength of the final 0.30 cm thick sample. (assume no widening occurs)

    a) 70% and 80ksi
    b) 90% and 87ksi
    c) 50% and 70ksi
    d) 40% and 67ksi
    e) 84% and 85ksi

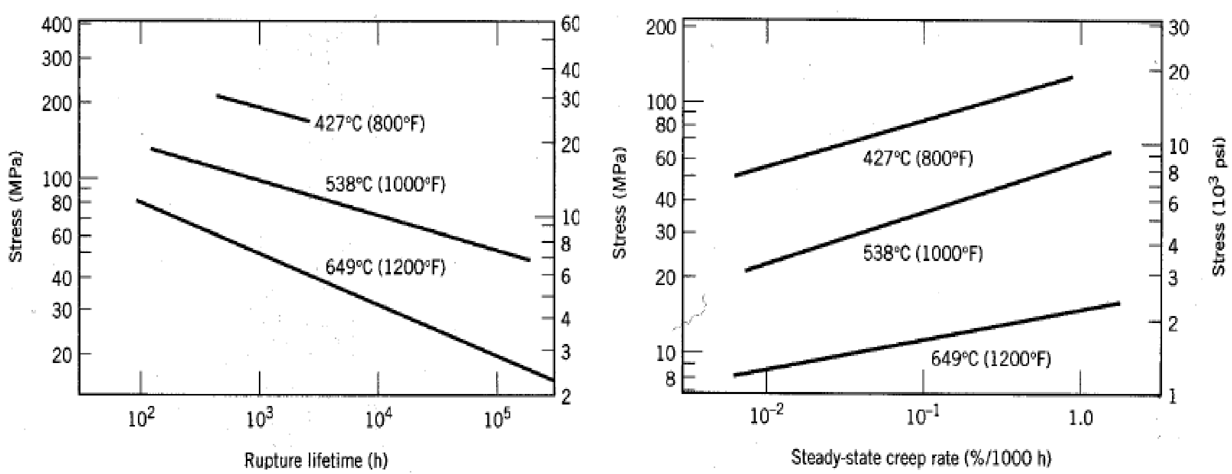


14. The elastic moduli in the 0° and the 90° directions of a unidirectionally reinforced composite (eg. unidirectional carbon fibres in an epoxy matrix) can be calculated using the iso-stress and iso-strain models. These models assume that:

    a) The fibres are free to slide in the matrix
    b) When the fibres are loaded in the iso-strain case, the fibres and matrix both elongate by the same amount
    c) When the fibres are loaded in the iso-stress case, the fibres and matrix both carry the same load
    d) Answers (b) and (c) are correct
    e) Answers (a), (b) and (c) are correct

15. Certain stainless steels, eg. 304 grade, when they have been welded and subject to moist environments can suffer from a problem known as "weld decay". In this situation:
   a) The zinc atoms in the braze metal used to make the joint leach out during the welding leaving only the copper atoms, making the joint weak.
   b) The carbon content is so high that regions of martensite form around the weld during cooling from the high weld temperatures and these regions make the stainless steel brittle in the weld.
   c) 304 stainless steel has 19% Cr and 9% Ni; the nickel and chromium atoms combine during the welding to form an intermetallic phase which precipitates out at the surface of the welds in the steel making the steel not "stainless" and prone to corrosion.
   d) The carbon in the 304 stainless steel is evaporated during the high temperatures of welding leaving it with very low carbon in the weld regions which make them susceptible to corrosion and thus "decayed".
   e) The carbon reacts with chromium during cooling from the welding forming chromium carbides which depletes the grain boundaries of chromium making them susceptible to corrosion.

16. A cylindrical component is fabricated from a low carbon-nickel alloy with a diameter of 20.0mm. The maximum load that may be applied for it to survive 10000 hours at 538°C is closest to (see the accompanying Figure):
   a) 22 N
   b) 35 N
   c) 22,000 N
   d) 30,000 N
   e) 35,000 N



17. For an aligned and discontinuous glass fiber-epoxy matrix composite with 25 volume % fiber, compute the longitudinal strength assuming that the average fiber diameter and length are 0.04 mm and 2 mm, respectively. The fiber-matrix bond strength is 50 MPa, fracture strength of the fiber is 6000 MPa and the matrix stress at fiber failure is 6 MPa.
   a) 1505 MPa
   b) 630 MPa
   c) 605 MPa
   d) 880 MPa
   e) 980 MPa

18. Which operation(s) should be performed to improve a steel component's resistance to fatigue crack initiation?
   a) decrease the radii at the corners of steps and keyways
   b) annealing of the surface
   c) carburizing (case-hardening)
   d) improve the surface finish (polish etc)
   e) c and d

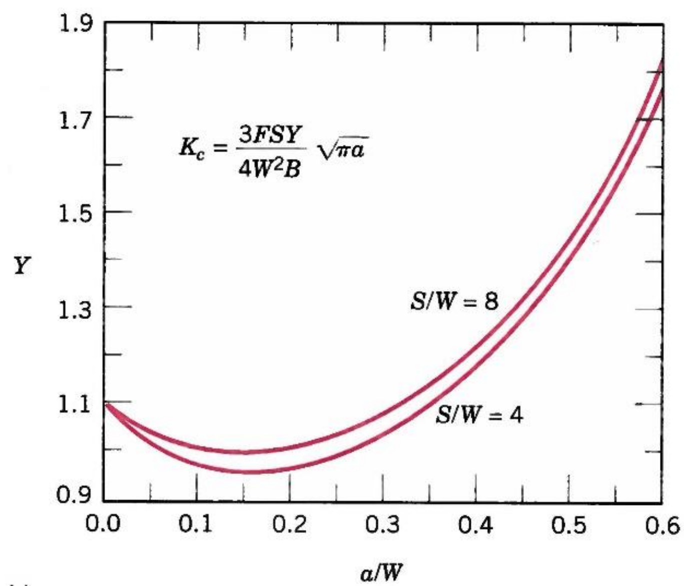
19. Which of the following criteria is not desirable when selecting creep resistant materials?
    a) a high melting point
    b) a high density of precipitates
    c) a high diffusion coefficient
    d) large grains or columnar structure
    e) solid solution strengthening

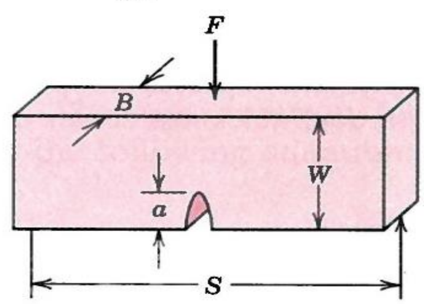
20. The data for a single crystal hypothetical metal is given below. If the applied tensile stress is 100 MPa, the resulting resolved shear stress is approximately:
    a) 0 MPa
    b) 7.5 MPa
    c) 43 MPa
    d) 50 MPa
    e) 86 MPa

Yield tensile strength = 130 MPa Angle between Burgers vector and close packed direction=0° Angle between the slip plane normal and tensile axis=30° Angle between the normal to the close packed plane and close packed direction=90° Angle between the slip direction and the tensile axis=85° Angle between the dislocation line and close packed direction=60°

21. Which of the following does not lead to an increase in yield strength in a ductile metal?
    a) forming a substitutional solid solution
    b) creating precipitates
    c) recrystallization
    d) work-hardening
    e) forming an interstitial solid solution

22. A quench and tempered, rectangular cross-section, steel bar is being used as a beam in a critical application. It is supported at either end with a span, S, of 160 mm. The beam is 20 mm high and has a thickness of 8 mm. It will be loaded at its centre with a downward force of 4000 N (in a three-point bending geometry). Unfortunately during quenching a vertical crack was formed across the bottom face of the beam, directly beneath the loading point. The crack has a depth of 8 mm into the bar. Using the accompanied graph, what is the geometrical loading constant, Y for this situation?
    a) 1.00
    b) 1.10
    c) 1.21
    d) 1.46
    e) 1.51





23. For the above question, the plane strain fracture toughness for this steel is 43 MPa.m$^{1/2}$ and the yield strength is 1200 MPa. If a load of 4000 N is applied, and using the equation given in the graph for K_c in 3 point loading;
    a) the stress intensity increases to the yield strength and the steel fractures.
    b) the stress intensity reaches 1000.7 MPa and the steel should not fracture.
    c) the stress intensity reaches a value of 28.8 MPa.m$^{1/2}$ and the steel should not fracture.
    d) the stress intensity reaches 38.9 MPa.m$^{1/2}$ and the steel will probably not fracture.
    e) the stress intensity exceeds the critical stress intensity factor, 43 MPa.m$^{1/2}$ so the steel will fracture.

24. For the above situation, the crack is noticed by an observant engineer but no spare bar or welding equipment is available. The equipment must be used so the cracked bar must be used so which of the following is the best option for the engineer until a spare can be shipped?

   a) The bar should be rotated vertically through 90^o clockwise.
   b) The bar should be rotated vertically through 90^o anti-clockwise.
   c) The bar should be rotated vertically through 90^o either way.
   d) The bar should be rotated vertically through 180^o.
   e) The bar should not be rotated but should only be used periodically by putting the 4000N load on each morning and taking it off at night (when the equipment is not being used).

25. For the above cracked steel bar, if instead of being loaded in bending, the bar is loaded in tension along its length, at what load will fast fracture be likely to occur? (Assume Y has a value of 2.0 in this case).

   a) 4,328 N
   b) 192,000 N
   c) 8,652 N
   d) 21,699 N
   e) 43,288 N

<u>**Questions 26-45:**</u> **True and false questions** *[0.5 mark each]*

26. A steel designated as an AISI 2010 steel indicates that this steel was developed in the year 2010.

27. The leak-before-burst principle is used in designing pressure vessels such that the critical crack size for fast fracture is at least as large as the wall thickness.

28. In high cycle fatigue, the number of cycles for crack initiation, N_i, is high and the number of cycles for crack propagation, N_P, is relatively low, whereas in low cycle fatigue the reverse is true.

29. If a steel component is subjected to a stress lower than its fatigue limit (endurance limit), it will fail by fatigue.

30. Martensite forms during the quenching of carbon steels from the austenitic phase at cooling rates slower than the critical cooling rate.

31. Welding of a steel component is unlikely to affect its fatigue behaviour.

32. Cast Irons contain more carbon than cast steels

33. Uni-directional carbon fibre-reinforced composites (with epoxy matrices) are used as structural components because of their high specific strength and stiffness and ability to withstand loading from different directions.

34. A single striation forms when a fatigue crack passes from one grain into the next.

35. Small grain size is usually preferred in metallic alloys because it gives higher yield strength. The exception to this is for creep applications where directionally-solidified columnar grains or single crystals are preferred.

36. FCC metals usually exhibit a more severe ductile-to-brittle transition at low temperatures than BCC materials.

37. The recrystallization temperature of a metal depends in part on the amount of previous cold working.

38. Aluminium shows a fatigue limit whereas tool steel does not.

39. A performance index of $P=\sigma^{1/2}/\rho$ means that all materials that lie on lines drawn in the materials selection charts with slope = 2 will perform equally for strength-per-mass basis. However, each line has a different value for the performance index itself.

40. High Strength Low Alloy (HSLA) steels are plain-carbon steels with low carbon contents that have been hardened by quenching.

41. An increase in the DBTT (ductile-brittle transition temperature) of a steel makes it more resistant to brittle fracture at lower temperatures.

42. A material with a high modulus of resilience is desirable when making springs

43. Work hardening is a good strengthening method for high temperature applications.

44. Magnesium or zinc blocks are attached electrically to large steel structures like ships to act as sacrificial anodes and provide a source of electrons to protect the steel from aqueous corrosion.

45. In solid solution strengthening, solute atoms of a different size from the solvent atoms hinder dislocation motion through interaction with the tension and compression zones of the edge dislocation.

PART B is on the following pages

PART B – ANSWER ALL QUESTIONS. PUT YOUR SOLUTION IN THE <u>SPACE BELOW THE QUESTION</u>.

<u>Question 46:</u> *{10 marks}*

(a) Compute the voltage at 25°C of an electrochemical cell consisting of pure nickel immersed in a 0.2 M solution of Ni^{2+} ions, and pure zinc in a 0.4 M solution of Zn^{2+} ions. (Using Tables below)

Electrode Reaction	*Standard Electrode Potential,* V^0 (V)
$Au^{3+} + 3e^- \longrightarrow Au$	+1.420
$O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O$	+1.229
$Pt^{2+} + 2e^- \longrightarrow Pt$	~+1.2
$Ag^+ + e^- \longrightarrow Ag$	+0.800
$Fe^{3+} + e^- \longrightarrow Fe^{2+}$	+0.771
$O_2 + 2H_2O + 4e^- \longrightarrow 4(OH^-)$	+0.401
$Cu^{2+} + 2e^- \longrightarrow Cu$	+0.340
$2H^+ + 2e^- \longrightarrow H_2$	0.000
$Pb^{2+} + 2e^- \longrightarrow Pb$	−0.126
$Sn^{2+} + 2e^- \longrightarrow Sn$	−0.136
$Ni^{2+} + 2e^- \longrightarrow Ni$	−0.250
$Co^{2+} + 2e^- \longrightarrow Co$	−0.277
$Cd^{2+} + 2e^- \longrightarrow Cd$	−0.403
$Fe^{2+} + 2e^- \longrightarrow Fe$	−0.440
$Cr^{3+} + 3e^- \longrightarrow Cr$	−0.744
$Zn^{2+} + 2e^- \longrightarrow Zn$	−0.763
$Al^{3+} + 3e^- \longrightarrow Al$	−1.662
$Mg^{2+} + 2e^- \longrightarrow Mg$	−2.363
$Na^+ + e^- \longrightarrow Na$	−2.714
$K^+ + e^- \longrightarrow K$	−2.924

GALVANIC SERIES

- Platinum
- Gold
- Graphite
- Titanium
- Silver
- [316 Stainless steel (passive)
- 304 Stainless steel (passive)]
- [Inconel (80Ni–13Cr–7Fe) (passive)
- Nickel (passive)]
- [Monel (70Ni–30Cu)
- Copper–nickel alloys
- Bronzes (Cu–Sn alloys)
- Copper
- Brasses (Cu–Zn alloys)]
- [Inconel (active)
- Nickel (active)]
- Tin
- Lead
- [316 Stainless steel (active)
- 304 Stainless steel (active)]
- [Cast iron
- Iron and steel]
- Aluminum alloys
- Cadmium
- Commercially pure aluminum
- Zinc
- Magnesium and magnesium alloys

(b) Write the resulting spontaneous electrochemical reaction.

(c) Certain ferrous alloys containing more than 11wt% Chromium are called “Stainless” steels. Explain why the chromium makes these steels “stainless”.

(d) In the Galvanic Series, Stainless steels (eg. 304) are listed twice; once near the top and once near the bottom. Explain the reasons for this. Are stainless steels "corrosion-proof"?

Question 47: *{24 marks}*
Below is a Table of metals and alloys with some of their properties. Select from this list, the metal or alloy that is best suited for each of the following applications. Give reasons for your choice(s) (i.e. what are the material requirements for this application); if there are two or more candidate materials suggest relative advantages of each.

a) Casing for a high-performance laptop computer.

Reasons:

Material:

b) Surgical scalpel blade (used for cutting skin etc.).
Reasons:

Material:

c) Drive shaft of common, mass-produced, 4-door car (eg. Honda Civic, Ford Focus etc)
Reasons:

Material:

d) Main strut for landing gear of large commercial aircraft (e.g. Boeing 787)
Reasons:

Material:

e) Fan blades (cold, 1st stage) for large turbofan aircraft engines eg. Rolls Royce Trent as used on Airbus A380 and Boeing 787

Material:

Reasons:

f) Base for milling machine in large workshop:

Material:

Reasons:

g) Body of water supply gate valve:

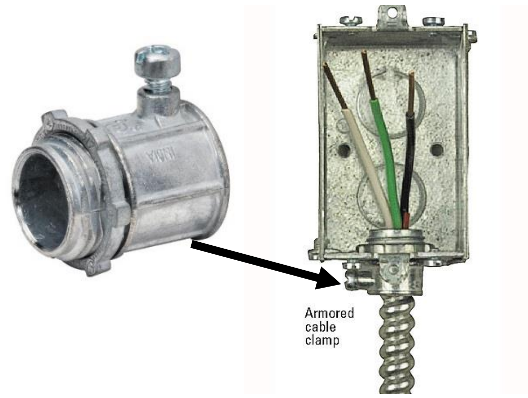
Material:

Reasons:

h) Cable clamp fitting for electrical outlet box:

Reasons:

Material:



Material	**ρ Mgm^{-3}**	**E GPa**	**Condition**	**σ_{TS} MPa**	**σ_Y MPa**	**%El.**	**K_{1c} MPa.m$^{1/2}$**	**Relative cost**
1010 Steel	7.85	207	Hot-rolled	325	180	28	≈ 140	0.8
1020 Steel	7.85	207	Hot-rolled	380	205	25+	≈ 140	0.8
1040 Steel	7.85	207	Hot-rolled	520	290	19+	≈ 120	1.0
4340 Alloy Steel	7.85	207	Quench & temper	1760	1620	12+	65	5.0
304 Stainless steel	8.00	193	Annealed	515	205	40+	≈ 90	4.0
440A Stainless Steel	8.00	193	Annealed Quench & temper	725 1790	415 1650	20 5	95 59	6.7
SAE G4000 grey cast iron	7.3	110-138	As-cast	276	n.a.	n.a.	≈ 6	1.9
60-40-18 Ductile cast iron	7.3	169	Cast & Annealed	414	276	18+	≈ 35	2.4
2024 Aluminum alloy	2.78	73	Heat-Treated T4	470	325	20	37	13
6061 Aluminum alloy	2.70	69	Heat-Treated T6	310	276	17	40+	7.6
7075 Aluminum alloy	2.81	71.7	Heat-Treated T6	570	505	11	24	10
238 Aluminum casting alloy	2.95	70	As-Cast	207	165	1.5	<20	5.1
AZ91D Magnesium alloy	1.81	45	As-cast	165-230	97-150	3	< 10	5.4
C11000 Copper	8.96	117	Annealed	220	69	45	≈ 100	7.4
C8440 Semi-red brass	8.7	90	As-Cast	235	105	26		5.1
Titanium - 6Al-4V alloy	4.5	110	Annealed	947	877	14	55-115	120
Zinc casting alloy Ag40A	6.6	50	As-cast	238		nil	12.3	2.0
Lead	11.35	14	As-cast	12	6	30		8.0
AS4 Carbon fibre/epoxy	1.58	142 10.3	-------- (0°) -------- -------- (90°) -------	2280 57	n.a.	1.5	n.a.	150

MECH 321 **EQUATION SHEET**

$U_r = \frac{\sigma_y^2}{2E}$ $\varepsilon_T = ln\left(\frac{l_i}{l_o}\right)$ $\varepsilon_{eng} = \left(\frac{l_i - l_o}{l_o}\right) = \frac{\Delta l}{l_o}$ $\sigma_T = k\varepsilon_T^n$ $(uniform\ plastic)$

$\sigma_T = \sigma(1+\varepsilon)$ $\varepsilon_T = ln(1+\varepsilon)$ $\sigma_y = \sigma_o + kd^{-1/2}$ $\%\ Cold\ work = \left(\frac{A_o - A_d}{A_o}\right) x100$

$\tau = \frac{M_T r}{J}$ $\gamma = \frac{r\theta}{L}$ $\tau_r = \sigma cos\lambda \cos\theta$ $\rho_c = V_f\rho_f + (1-V_f)\rho_m$ $L_c = \frac{\sigma_f d}{2\tau_c}$

$E_{c1} = E_f V_f + E_m V_m$ $E_{c2} = \frac{E_f E_m}{E_f(1-V_f)+E_m V_f}$ $\sigma_{cd}^* = \sigma_f^* V_f\left(1 - \frac{l_c}{2l}\right) + \sigma_m'(1-V_f)$

$\sigma_{cd'}^* = \frac{l\tau_c}{d} V_f + \sigma_m'(1-V_f)$ $\sigma_{cl}^* = \sigma_f^* V_f + \sigma_m'(1-V_f)$ $\sigma_{c2} \approx \frac{\sigma_m}{2}$

$\sigma_{max} = 2\sigma_o\left(\frac{a}{\rho}\right)^{1/2}$ $K_T = \frac{\sigma_{max}}{\sigma_o}$ $\sigma_c = \sqrt{\frac{2E\gamma_s}{\pi a}}$ $(brittle)$ $\sigma_c = \sqrt{\frac{2E(\gamma_s+\gamma_p)}{\pi a}}$ $(plastic)$

$G_c = \frac{K_{1c}^2}{E}$ $K_{1c} = Y\sigma\sqrt{\pi a}$ $B \geq 2.5\left(\frac{K_{1c}}{\sigma_y}\right)^2$

$\sigma_{amplitude} = \frac{\sigma_{range}}{2} = \frac{\sigma_{max}-\sigma_{min}}{2}$ $\sigma_{mean} = \frac{\sigma_{max}+\sigma_{min}}{2}$ $\sigma_{range} = \sigma_{max} - \sigma_{min}$

$\frac{da}{dN} = A(\Delta K)^m$ $where$ $\Delta K = Y(\sigma_{max} - \sigma_{min})\sqrt{\pi a}$

$N_f = \int_{a_o}^{a_c} \frac{da}{A\left(Y\Delta\sigma\sqrt{\pi a}\right)^m} = \frac{1}{A\pi^{m/2}\ (\Delta\sigma)^m}\int_{a_o}^{a_c}\frac{da}{Y^m a^{m/2}}$ $\sigma_{thermal} = \alpha E\Delta T$

$\dot{\varepsilon} = Ae^{-Q/RT} = k\sigma^n e^{-Q/RT}$ $P_{(Larson-Miller)} = T(C + \log t)$

$\Delta V = (V_2^o - V_1^o) - \frac{RT}{nF} ln\left[\frac{M_1^{n+}}{M_2^{n+}}\right]$ $\Delta V = (V_2^o - V_1^o) - \frac{0.0592}{n}\log\left[\frac{M_1^{n+}}{M_2^{n+}}\right]$ $CPR = \frac{KW}{\rho At}$

$\boldsymbol{r} = \frac{\boldsymbol{i}}{\boldsymbol{nF}}$

Constants

R= 8.314 $J.mol^{-1}.K^{-1}$ F = 96,500 $C.mol^{-1}$ $N_A = 6.023 \times 10^{23}$ molecules/mole