AE1108 - Aerospace Materials

24 January 2019

13.30 – 16.30

S&C-Hall 3

COMPACT ANSWERS VERSION
TO HELP STUDENTS PREPARE FOR THE RESIT

(feedback comments in italics and in blue)

Your name:

Your student number:

- Check if you have received all of the 16 pages and write your name and student number at the top of every page.
- This exam consists of 10 questions concerning different topics. Each question contributes an equal amount to the total score. Fill in your answer on the space provided under each question or use the back side of the previous page
- Please read the questions carefully and in answering the questions always make your line of reasoning clear (even if you do not know how to solve the question numerically).
- Please hand in this exam on or before 16.30
- The use of a simple hand-held calculator (without memory functions) is allowed, but consultation of internet is strictly forbidden.
- **Two exam paper review sessions will be organised and announced via Brightspace. Admission will be only by prior reservation.**

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STUDENT NAME: **STUDENT NUMBER:**

Question 1: Concepts and terminology

Please mark the correct answer for each of the 10 statements.

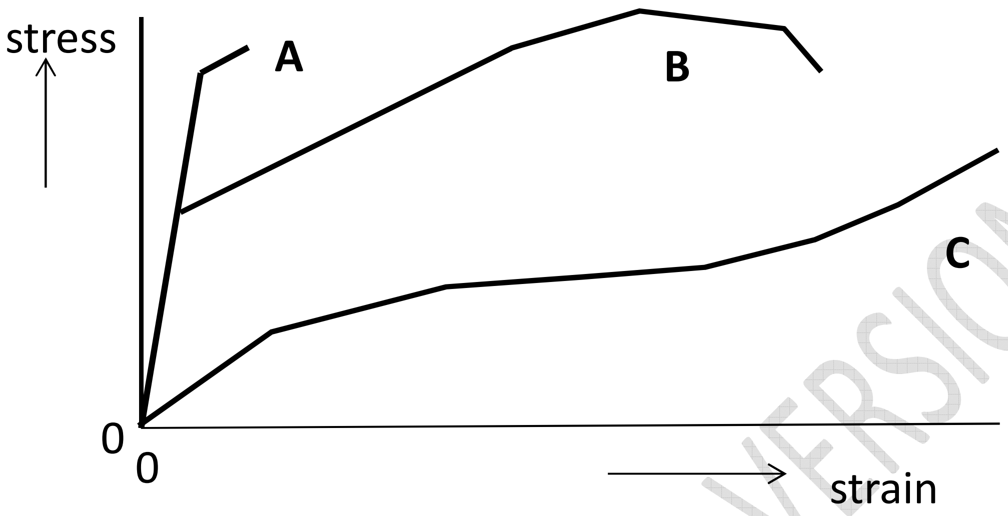
Ambiguously marked answers will be graded as 'incorrect'. Each wrong answer will lead to a reduction of 20% of the maximum grade for this question (provided the remaining score is still positive)

	statement	True	False
1	A material with a high Young's modulus is always a brittle material		X
2	Thermoset polymers cannot deform plastically because they have no dislocations		X
3	Thermoplastic polymers of a given composition will always have the same elastic modulus at a given temperature		X
4	The grain size has a strong effect on the yield strength of most metals as there is an abrupt change in the slip plane orientation across the grain boundary	X	
5	Ceramics will always show a brittle behaviour as their dislocations are effectively immobile	X	
6	Kerosene, being an non-ionic liquid, will promote corrosion in aluminium fuel tanks		X
7	Amorphous glasses will show a well-defined melting point		X
8	The strength of a product containing a crack is determined by the crack dimension and the ultimate tensile strength of the material it is made of		X
9	Polymers become transparent when cooled below their glass transition temperature		X
10	Creep deformations in metals and polymers are time-independent		X

STUDENT NAME: **STUDENT NUMBER:**

Question 2: Interpretation of the stress-strain curve of an arbitrary material

Below you will find the schematic stress-strain curves of three materials (marked A, B and C), all failing abruptly at the end of their stress strain curve.



A. If material A is a steel, argue which other (or none) of the other materials could be a steel too.

Steel B can be a steel to since it has the same E-modulus as material A.

Yield stress, UTS or strain hardening comments are not relevant and such answers were graded as 'incorrect'

B. If material A has a modulus of 200 GPa and a Yield strength of 1000 MPa, what will be the imposed strain at the onset of plastic deformation?

Simple calculation σ = E. ε, will give ε= 0.005 or 0.5%

All answers in which the strain was expressed in mm were graded as 'incorrect'

C. If all is well the strain you calculated in subquestion 2.B) is different from 0.2%, the strain value which historically has been used to detect the occurrence of plastic deformation. Explain how both your answer in 2.B and the convention can be correct.

The strain of 0.5% is the elastic strain preceding the onset of plastic deformation and is measured under load. The strain of 0.2% is the plastic strain recorded after removal of the load.

All answers commenting of inaccurate measurements or defects in the material were graded as 'incorrect'

D. Which material of the three materials marked in the graph would you use for a mechanical spring? (argue your case)

The key criterion for a material to be used as a spring is its ability to store as much elastic energy as possible. The amount of stored elastic energy is the area below the stress strain curve (up to the yield point). This is highest for material A.

Some credits were given for partially correct answers leading to material A depending on the argumentation. Answers leading to Material B or C were graded as 'incorrect'

E. Which material (of the 3 sketched in the graph) would you use as material for the fender of a passenger car such as to minimise injuries to a pedestrian on impact? (explain why you selected this material)

For the fender minimising the damage to a pedestrian the key feature is the low modulus in combination with an adequate failure strain, so material C.

Answers leading to steel B on the basis of the total storable energy were graded as 'incorrect' because of the high modulus of the material. Answers leading to Material A were rarely given but are 'incorrect' too. Historically fenders were made out of material B but then the idea was to protect the car and the passengers in the car as much a possible. Traffic Fatality analysis showed that more people die in car-pedestrian accidents than in car-car accidents so the fenders of all modern cars are from polymers with the appropriate low stiffness for the initial impact phase. The steel frame itself will handle car-car collisions.

STUDENT NAME: **STUDENT NUMBER:**

Question 3: Structure of materials

A. Almost all metals are crystalline, i.e. have a crystal structure. Explain the difference between the crystalline unit cell and a grain.

A unit cell is the smallest possible entity fully showing the mutual arrangement of the atoms for that structure. A grain is the set of connected unit cells sharing a common orientation.

In grading this question I looked for the two underscored word combinations. Grain size is not relevant nor is the reference to grain boundaries

B. Polymers and elastomers both can be fully amorphous and have more or less the same composition. What is then the critical difference between the two with respect to their molecular structure?

An elastomer will always have a low but non-zero crosslink density, while polymers can have no crosslinks (thermoplasts) or have many crosslinks (thermosets)

C. Polymeric foams and glass fibre reinforced polymer composites are both examples of composite materials. What is the role of the air in a foam and what is the role of the glass fibre in the composite material, when aiming to control the stiffness of the material?

The inclusion of air in a polymer (making it a foam) lowers the stiffness, while inclusion of glass fibres raises the stiffness.

D. What is the difference between an alloy and a pure metal?

A pure metal contains only one type of metallic atoms (or one chemical metallic element), while alloys contain at least two types of metallic elements.

In case the answer contained the word 'molecule' it was graded as 'incorrect'. In case the answer referred to C as an alloying element for steels the answer was graded as 'correct'

E. Many aluminium alloys for aerospace applications are precipitation hardened. What is a precipitate and how does it make the aluminium alloys harder?

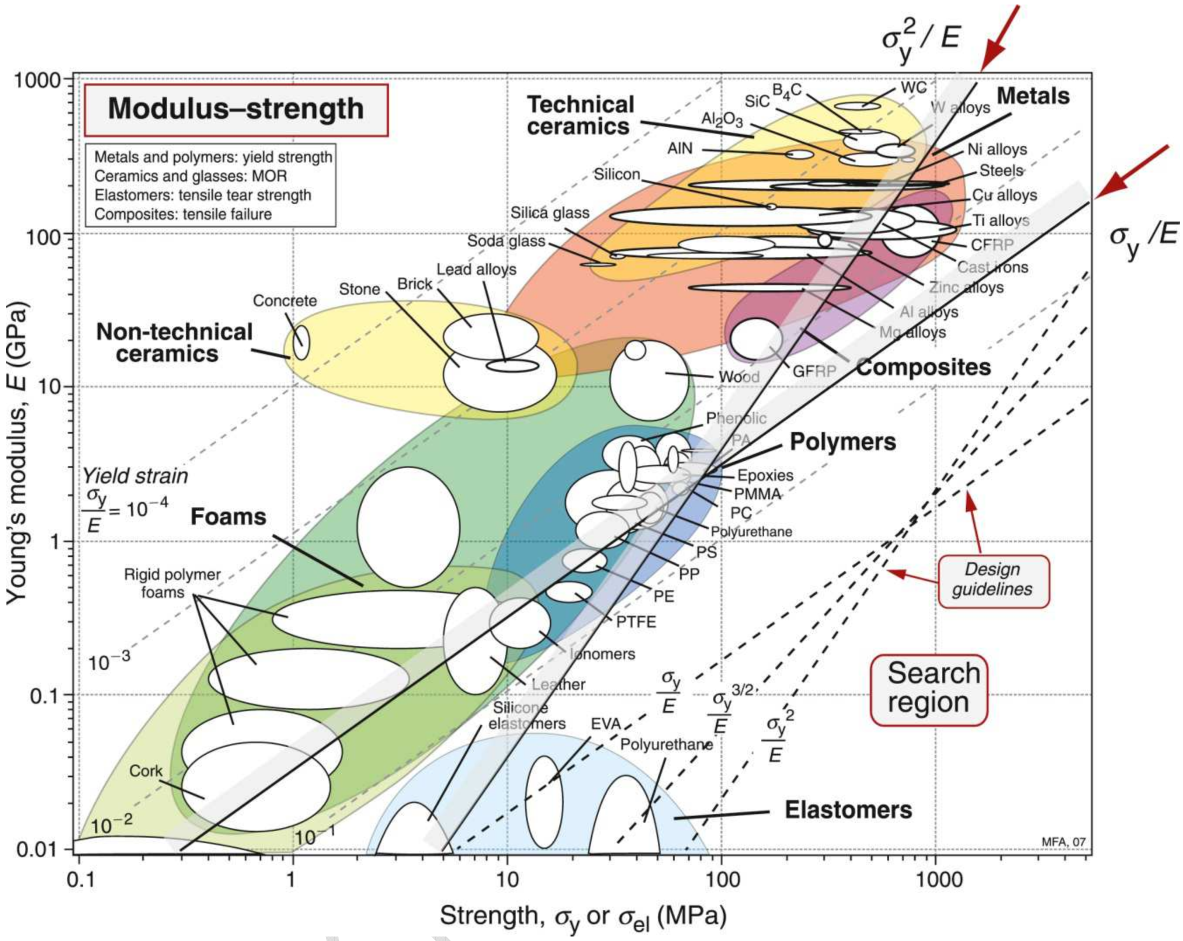
A precipitate is a cluster of atoms (of a different chemical nature than the matrix) arranged in a crystal structure different from that of the matrix. The precipitate hinders the motion of dislocations and thereby raises the yield stress (makes the metal harder).

In case the answer contained the word 'molecule' or 'big atom' the answer was graded as 'incorrect'. In case it contained the word 'particle' or alike, it was generally graded as 'correct', unless the description was way off the correct answer

STUDENT NAME: **STUDENT NUMBER:**

Question 4: On the use of Ashby material plots and material indices

Below you will find one of the so-called Ashby plots which will make it easier to quickly compare the merits of widely different material families. This one is a plot of the Young's modulus versus the yield strength.



Let us consider the material index concept for the selection of the best material for an *elastic hinge.* For this you need the equation linking the maximum filament strength as a function of the radius of curvature R, the thickness t, and the Young's modulus of the material.

$\sigma = E.t / (2. R)$

A. Derive the material index for an elastic hinge.

Rewriting this equation shows that the smallest radius which can be reached requires the highest value of σ/E. This is therefore the MI, so MI = σ_y/E.

B. Using this MI, select the best material for elastic hinges, setting as secondary constraint that the yield strength must be between 10 and 20 MPa. Describe your selection process below in words and mark the critical MI line in the plot on the previous page.

To find the ideal material, mark two vertical lines hitting the x-axis at 10 and 20 MPa and lower the line σ_y/E to the lowest position where it will hit a named material field and that marks the preferred material EVA.

In most of the examples in class and in the book you had to move the line up to get better MI values. Please note that here better values are found when you lower the line (i.e. move up to higher yield stress values). Answers obtained by not moving the line (leading to the selection of FTFE) or moving the line up (leading to lead alloys as the preferred material) are graded as 'incorrect'

C. What is the best material for the elastic hinge in case two constraints are applied: the yield strength should be close to 15 MPa and the modulus should be around 0.8 GPa? Again, describe the selection process below and mark in the plot on the previous page the critical MI line.

In this case the MI line plays no role at all, and the question only aims to see if the student can 'read' the Ashby map. So you draw a vertical line crossing the x axis at 15 MPa and a horizontal line at 0.8 GPa. The material closest to the point is PE (and/or above any of the target values), and that is the correct answer.

I discovered that 5-10% of the students apparently can not read a logarithmic scale and put the lines at rather different positions than at 0.15 MPa and 0.8 GPa.

D. How much better (as material for an elastic hinge) is the material you selected in answer B than that you selected in answer C?

The how much better questions is related to understanding the significance of the MI. So the correct answer is $MI_{EVA} / MI_{PE} = (14.\ 10^{-3}/\ 0.02)\ /\ (20.\ 10^{-3}/\ 0.8) = 0.7/\ 0.025 \cong 30$

In case the students had used a wrong MI or had selected a wrong material (such as bricks or lead) but compared the relative material performance based on using MI values, the subquestion was graded as 'correct'

E. When the hinges are made out of the material you have selected in question B, real life practice will show that the hinges will fail after a short time use. Which other material property should have been taken into account too?

Doors have to be opened and closed many times, so the correct answer is 'fatigue strength' or 'endurance limit.

The answer 'fracture toughness' is graded as 'incorrect' as that parameter only has relevance in case of a cracks reported to be present.

Question 5☺ Deriving the properties of composites

The longitudinal Young's modulus of a unidirectional composite containing continuous fibres has been derived to be
$E_{compos} = f. E_{fibre} + (1-f) E_{matrix}$,
where the parameters have their usual meaning.

A. Strictly speaking the above equation has been derived assuming perfect bonding between the fibre and the matrix. Does the above equation change, in case of very weakly bonded or even de-bonded fibres? (show the calculations).

The degree of bonding plays no role for a longitudinal modulus of a UD composite. (i.e. the applied load or strain is perfectly parallel with the fibres). The strain in the fibre and the matrix is the same $\varepsilon = \varepsilon_{composite.}$ The load taken up by the fibres is $f.E_f.\varepsilon$, while the load taking up by the matrix is $(1-f).E_{matrix}.\ \varepsilon$ (assuming a total unit cross sectional area of 1). Hence, also for debonded fibres $E_{compos} = f. E_{fibre} + (1-f) E_{matrix}$

B. Derive the equation for the lateral (i.e. perpendicular to the plates) modulus of a laminate consisting of 10 plies of metal and 10 plies of polymer (all plies having the same thickness) in case of perfect bonding.

Comparable to the case above, but now the stress σ in both materials is the same (instead of the strain). This leads to the equation $\varepsilon_{compos} = f .(\sigma / E_{metal}) + (1-f). (\sigma / E_{polymer})$. Inserting the volume fraction f= 0.5 (the number of plies does not play any role) leads to the answer
$E_{composite} = 2 E_{metal}.E_{polymer}/ (E_{metal} + E_{polymer})$.

C. For the same topology as for question 5B, what will be the lateral stiffness value in case of *non-bonding* between the two materials, and the modulus of the metal plies is 90 GPa and that of the polymer plies 1 GPa?

In case there is no bonding, the load which can be transferred in tension is zero (=0) and the load can only be transferred in compression. So $E_{debonded}$ = 0 GPa in tension and 1.9 GPa in compression

STUDENT NAME: **STUDENT NUMBER:**

Question 6: Fracture mechanics[8.8]

A. What is the difference between the fracture toughness and the fracture strength?

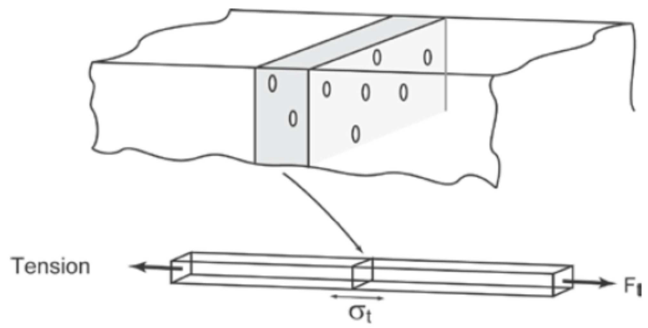
Fracture toughness enables calculating the fracture stress in case the sample contains a crack. The fracture strength (UTS) describes the maximum load divided by the cross sectional area in case of an un-cracked sample (having a uniform cross section, i.e. no stress concentrations).

B. Derive the units in which fracture toughness and fracture strength are expressed and show that they must be different.

Fracture stress is load over area and hence is in Pa (or MPa or GPa)

Fracture toughness (recalling the equation $K_{ic} = Y\, \sigma_{fracture}\, (\pi.\, c)^{1/2}$ is expressed in Pa.$m^{1/2}$

C. Two long wooden beams of square cross section t x t = 0.1 m are butt-jointed using an epoxy adhesive. The adhesive was stirred before application, trapping air bubbles that, under the pressure in forming the joint, deformed to flat, penny shaped cracks of 2 mm diameter. In your calculations assume the Y factor in the fracture equations to be 1, the fracture toughness of the epoxy to be K_{1c} = 1.3 MPa.$m^{1/2}$ and the UTS of the epoxy to be σ_f = 100 MPa. The adhesion strength of the epoxy to the wooden beam may be considered to be infinitely high.



Calculate the failure load of the beam with the epoxy connection when it is loaded in uniaxial tension (assuming failure will take place in the epoxy).

Realizing that the pores are to be regarded as small cracks (with the pore size being twice the crack dimension) and inserting the values given into the equation $K_{ic} = Y\,\sigma_{fracture}\,(\pi.\,c)^{1/2}$, and multiplying the stress with the cross sectional area of 0.1x0.1 m yields 232 kN.

In case only the stress value was calculated (i.e. not multiplied with the area) the answer was graded as 'incorrect'.

In case the pore diameter was taken as the dimension of the crack, the answer was graded as 'partially correct'

In case the students interpreted the area reported as t x t = 0.1 m to mean that the area was 0.1 m² the calculated load was 10 times higher but also this solution was graded as 'correct'

D. Calculate the maximum pore size of the bubbles which would not lead to a lowering of the failure strength of the beam when loaded in tension.

In case the pores do not lead to strength reduction, it means the failure stress was 100 MPa. Inserting this into the equation $K_{ic} = Y\,\sigma_{fracture}\,(\pi.\,c)^{1/2}$ and inserting the value for K_{1c} the calculated crack size is 0.05 mm and the corresponding maximum pore size is 0.1 mm.

Answers in which the crack size was presented as the pore size were graded as 'partially correct'

All answers leading to a value bigger than 2 mm were graded as 'incorrect' because that answer would be inconsistent with question C.

Question 7: Facture and fatigue[9.10]

An aluminium alloy for an airframe component was tested in the laboratory under an sinusoidally applied stress with a mean stress of zero MPa per cycle. The alloy failed under a stress range of $\Delta\sigma$ = 280 MPa after 10^5 cycles. Under a stress range of 200 MPa (again with zero mean stress) the alloy failed after 10^7 cycles. Assume that the fatigue life time of the alloy can be represented by:

$$\Delta\sigma\ N_f^{\,b} = C$$

Where b and C are unknown constants and N_f is the number of cycles to failure.

A. Calculate the number of cycles to failure for a component subjected to a stress range of 150 MPa (again zero mean stress).

Inserting the values for the reference cases in the above equation leads to $280\ (10^5)^b = 200\ (10^7)^b = C$, which means we have two equations with two unknowns, so can be solved.

This leads to b = 0.073 and C = 649 MPa.

Inserting now the stress value 150 MPa yields $N_f = 5.2\ 10^8$

B. An aircraft using the above airframe components has encountered an estimated $4.\ 10^8$ cycles at a stress range of 150 MPa. It is desired to extend the life time of the airframe by another $4.\ 10^8$ cycles by reducing the load. Uses Miner's rule to calculate the new stress range to achieve this life extension.

Miner's rule states that failure occurs when the sum of the fractional lives is.

The fractional live at 4.10^8 at the stress of 150 MPa is 4/(5.8) = 0.69. So the fractional life time at the new (lower) should be 0.31. With actual life time at this stress defined as $4.\ 10^8$, we now obtain the complete life time at this stress level $12.9\ 10^8$ cycles. With the staring Basquin equation and the know and derived values we calculate a new stress range of 137 MPa.

Answers derived on the basis of a wrong estimate of N_f as calculated in A, following the correct procedure were graded as 'correct'.

Answer yielding a value > 150 MPa were graded as 'incorrect' anyway because of internal inconsistency.

STUDENT NAME: **STUDENT NUMBER:**

Question 8: Thermal properties and behaviour[12.10]

Square porcelain tiles are to be manufactured with a uniform layer of glaze, which is thin compared to the thickness of the tile. The prebakes tiles and the glaze are fired at a temperature of 500°C and then cooled slowly to room temperature, 20°C. At the firing temperature the porcelain becomes a solid ceramic and the glaze flows like a viscous melt.
Two tile types are to be manufactured: the first is decorative, using tension in the surface to form a mosaic of cracks, the second one is to have a high strength by making the glaze induce compression in the surface to resist surface cracking.

A. Based on an analysis of the thermal stress as a function of the material properties and the temperature change and the CTE values below, select the most suitable glaze (A, B or C) for each of these applications and justify the answer by calculation. If none of the glazes lead to the required result under the required conditions lead to the desired result, please state so. The glazes have comparable mechanical properties and only differ in their CTE.

Young's modulus of glaze E = 90 GPa, Young's modulus of the porcelain E = 400 GPa, Poisson's ratio of glaze, ν = 0.2, tensile failure stress of glaze = 10 MPa

Coefficients of thermal expansion: $\alpha \times 10^{-6}$ (K^{-1})	
Porcelain	2.2
Glaze A	1.5
Glaze B	2.3
Glaze C	2.5

For this the students had to back to the equation for thermal stress of bound coatings :

$\sigma = E/(1-\nu) \;.\; (\alpha_1 - \alpha_2) \;.\; \Delta T.$

Inserting the values given and realizing the a less expanding glass (than the substrate) would lead to compressive stresses (i.e. negative stresses) leads to the stress values for glass A, B and C of -37 MPa, + 5 MPa and + 16 MPa. So glass A is the only one suitable for raising the strength of the tile and glass C is the only one leading to cracks in the glass (i.e. making the decorative tile).

Other approaches to calculate stresses via strain analysis were fine too.

In case the answer was derived without realizing that it is the difference in CTE rather than the absolute CTE values, it is impossible to reach the correct answer.

B. As firing furnaces bring about quite some environmental burden, it is desired to set the temperature of the furnace as low as possible. For the decorative tiles, what is the minimum furnace temperature, when selecting a temperature margin of 30 ^{0}C with respect to the conditions where cracks just may start to form (taking into account that tiles and glazes are ceramics and hence their strength is not well defined but shows a Weibullian distribution)

Apply the above equation and find that ΔT= 301 ^{0}C. With a reference room temperature of 20 ^{0}C and a margin of 30 ^{0}C the final furnace temperature should be set to 351 ^{0}C (or comparable values).

In case the student used a different glass than C but used a solid protocol the answer was graded 'correct'.

In case the answer presented was > 500 ^{0}C the answer was graded as 'incorrect' because of inconsistency with question A.

Question 9: Corrosion and degradation[17.24]

A. What is meant by the Limited Oxygen Index?

The percentage of oxygen in the atmosphere required to produce a stable burning of the material

Answers listing the oxygen content in the material itself were graded as 'incorrect'.

Answers linking LOI to oxidation or corrosion instead of to burning were graded as 'incorrect'

B. In the space shuttle the LOI value of all non-metallic or ceramic materials in use is 36 or higher. What is the consequence thereof, knowing that the air composition in ISS in recent years has been set to 21% oxygen, 78% N2 and 1 % CO_2?

The oxygen concentration in ISS is 21% while the materials need 36 % to keep burning. So any fire at ISS is self-extinguishing.

Some student correctly pointed out that I use both the word ISS and the space shuttle. Sorry for the confusion. In the few exam papers where it seemed to have caused confusion, I graded the answer in favour of the student.

C. A steel gutter is used to guide splashing sea water away from a hangar situated next to the sea. The gutter is copper plated (coated) to prevent it from corroding. If the copper coating is damaged by a dropped pebble such that the steel is locally exposed, will this lead to rapid local corrosion or will the coating maintain its protective function even at and near the damage site?

(You may want to consult the Standard Reduction Potential table on the next page).

Given the fact that the four criteria for electrochemical corrosion (an anode and a cathode having a different redox potential, an electrolyte and a closed electrical circuit) are met, corrosion will take place. The steel is the less noble element, so will dissolve. As the steel area is small in comparison to the copper area, there will be a high corrosion current density and the dissolution will go rather fast. So the coating will lose its protective function

Answers taking steel to mean stainless steel were graded as 'incorrect' as it showed a lack of elementary material performance perception

D. If the steel gutter instead was coated with a thin zinc layer (galvanized or galvanealed) what would be the consequence of such a local damage site exposing the steel?

For the same reasons as in C, electrochemical corrosion will take place, but now the zinc will corrode away and the steel will remain unattacked. As the Zn area is very big in relation to the exposed steel area, the corrosion current will be low and the dissolution will be slow. The gutter remains protected against corrosion as long as there is a sizeable Zn coated area left.

STUDENT NAME: **STUDENT NUMBER:**

Question 10: Environmental consequences 20.9.14

A. Express in one sentence the most energy intensive phase (in terms of consuming fossil energy) or each of the following products: State your 5 answers in the space here below.

- An electrical toaster

It will consume most of its energy during the use phase

- A bicycle

It will consume most of its energy during the construction /fabrication phase

- An airplane

It will consume most of its energy during the use phase

- A wind turbine

It will consume most of its energy during the construction /fabrication phase

- A ski lift

It will consume most of its energy during the use phase

B. Window frames can be made out of aluminum or PVC. Assuming both types of window frames to have the same dimension which type of window frame is energy wise, environmentally most friendly? Please note that the recycling rate of aluminum can be varied between 0 and 100 %, while PVC window frames are always made out of 'fresh' PVC. If you argue for aluminium frames, please deduce the minimum recycling level of the aluminium required to reach an energy beneficial solution.

Material	Density (kg/m^3)	Embodied energy (MJ/kg)
PVC	1440	82
Fresh aluminium	2700	210
100 % recycled aluminium	2700	26

First calculate the embodied energy per m^3 by multiplying the density with the volumetric embodied energy (the window frames are to have a certain volume rather than a certain weight) and find that for PVC, fresh aluminium and 100 % recycled aluminium the values are 1.18, 5.7 and 0.72 10^5 MJ/m^3. Fully recycled aluminium is therefore the preferred material.

Comparing the embodied energy of PVC with that of aluminium with an unspecified fraction recycled material shows by simple (linear) interpolation that the minimal recycled fraction has to be 90%.

Answers where students first identified the correct answer and then changed their mind to PVC for qualitative/political reasons were generally graded as 'incorrect'.

Switching to PVC by claiming that 90% recycled aluminium is not realistic was rejected too as 100% recycled Aluminium is a known feedstock grade in the extrusion market.