National Exams December 2010
98-Met-B5 Metal Fabrication
3 hours duration

NOTES:

1. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer page, a clear statement of any assumptions made
2. Candidates may use one of two calculators, the Casio or Sharp approved models. This is a closed book exam.
3. All questions should be answered or attempted.
4. They are four questions and they are all of equal value.
5. Some common formulae are given at the end of the examination as well as material property tables.

Question 1 (20 marks)

a) Sketch how the temperature profile and structure of the casting will vary from the mould wall into the casting. Indicate both the liquidus and solidus temperatures. (3 marks)

b) The Figure below shows a cylindrical riser attached to a casting. Estimate the relative solidification times for the casting section and the riser. Determine whether the riser will be effective. Show all calculations. (7 marks)

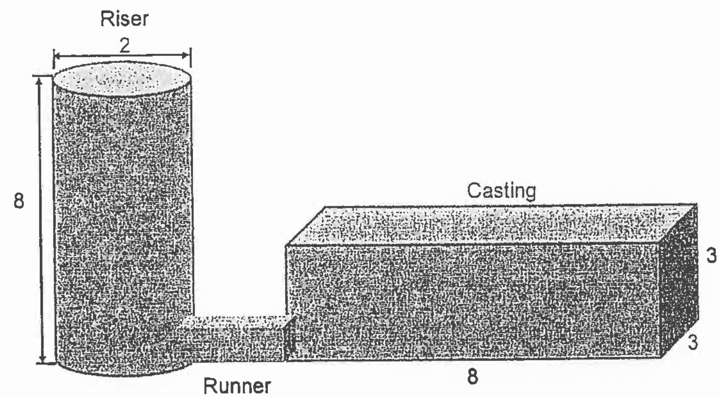

Figure 1 – Schematic of a casting set-up showing the riser, runner and casting mould as well as the dimensions. Note: All dimensions are in cm

c) Why are sprues normally tapered instead of having the same cross sectional area at the top and bottom? (3 marks)

d) Using the Sn-Pb phase diagram shown in Figure 2. Calculate the amount of liquid and solid (α phase) present at 200°C for a Sn-30%Pb alloy. What is the composition (%Pb) of the liquid phase (7 marks)

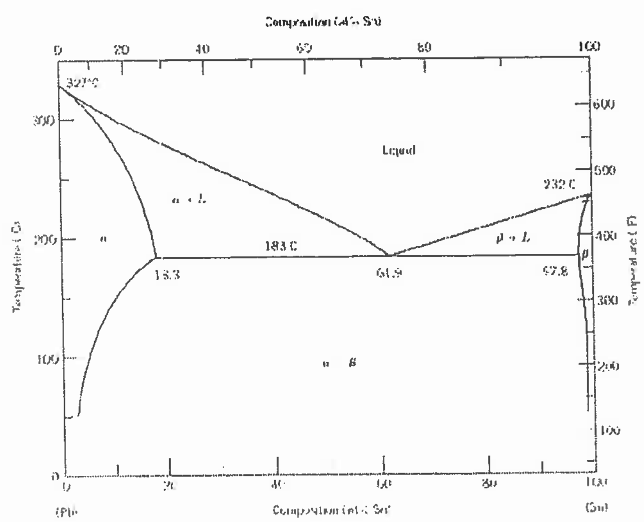

Figure 2 – Pb-Sn phase diagram.

Question 2 (20 marks)

a) Calculate the temperature rise in a 1008 steel (ρ=7.8×10^{3}kg/m^3, C=4.6×10^{2}J/kg/K) which is cold rolled from 4 to 2.5 mm thickness. It can be assumed that 98% of the external work is converted into heat. What happened to the remaining 2% of the external work? (2 marks)

b) A bar on length l_o is uniformly extended until its length l = 2l_0. Compute the values of engineering and true strain for this extension. (2 marks)

c) A right circular cylinder of SAE 1045 steel, of initial height 20 cm and diameter 20 cm, is to be upset at 1000°C between un-lubricated platens to reduce its height to 10 cm. The total deformation will occur over a 2 second interval at constant ram speed. Assume sticking friction conditions apply. The melting point for SAE 1045 steel is 1500°C. (10 marks total)

   i. Sketch a pressure versus position curve across the specimen diameter at the end of forging. Indicate on the diagram the work required to overcome friction as well as the work required to deform the material. (2 marks)

   ii. What minimum size of press (hydraulic) is required in KW? (6 marks)

   iii. If the overall efficiency of the operation is 30 per cent, approximately what power is required to drive the press? (2 marks)

d) You are working in a company where coils of steel strip are cold rolled in a mill with polished 25cm diameter work rolls made from 0.5% carbon steel. There is a market demand to produce strip with a lower thickness than you can obtain with your current mill setup. In order to achieve additional strip thinning, the following alternatives have been proposed. Please evaluate each of them and discuss whether or not they would be a practical solution. (6 marks total)

   i. reduce lubrication or slightly roughen the roll surface (1/2 mark)
   ii. reduce the roll speed by a factor of two (1/2 mark)
   iii. anneal the strip before each rolling pass (1 mark)
   iv. heat the strip to 900°C as it enters the rolls (1 mark)
   v. apply a front tension equal to 50% of the final yield stress of the strip (1 mark)
   vi. replace the 0.5% carbon steel rolls by tool steel rolls (1 mark)
   vii. change to 10cm diameter work rolls (1 mark)

Question 3 (20 marks)

a) Which material steel (Yield Strength = 150 MPa, Elastic Modulus = 200 GPa), aluminum (Yield Strength = 200 MPa, Elastic Modulus = 70 GPa) or Titanium (Yield Strength = 300 MPa, Elastic Modulus = 120 GPa) would you expect to give you a largest amount of springback if the sheet thickness and bend radius were the same? Show all calculations (4 marks)

b) Estimate the strain at which necking will occur for aluminum alloy AA1100 during uniaxial tension (2 marks)

c) A set of 1.0 mm thick sheet metals are being evaluated for forming operations. Samples were taken from the sheet and tested in uniaxial tension. Tests were performed in three directions with respect to the rolling direction, i.e. 0, 45 and 90°. The tensile tests were stopped at a true strain of 0.2 which, in all cases, was prior to the onset of necking. The measured true width strains are given in the Table 1 below. (14 marks total)

Table 1 – Tensile test data for some different metal sheets.

Material	Yield strength (MPa)	width strain, 0°	width strain, 45°	width strain, 90°
Low carbon steel	200	-0.117	-0.123	-0.113
IF steel	105	-0.138	-0.131	-0.141
Aluminum	125	-0.095	-0.092	-0.0975

i. Calculate the R-values; i.e. R_0, R_{45}, R_{90} and $\bar{R}$. (2 marks)

ii. Rank the three materials with respect to their tendency to form ears during deep drawing. Be quantitative in your answer. (2 marks)

If the IF steel sheet is chosen for the forming operation (yield strength = 105 MPa, tensile strength = 125 MPa and work hardening value, n = 0.35), estimate the following (use Figure 3 shown below as needed).

iii. The largest circular blank diameter that can be used to draw a cup with a diameter of 10 cm. (4 marks)

iv. The press force required to effect the draw. (2 marks)

v. The blanking force to cut the blank. (2 marks)

vi. State the consequences of using a: too low or b: too high a blank-holder pressure in deep drawing (2 marks)

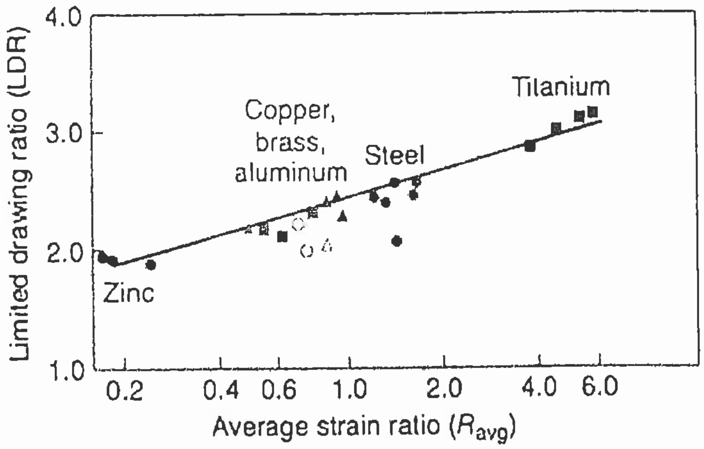

Figure 3 – Effect of average normal anisotropy ($\bar{R}$) on Limiting Draw Ratio (LDR).

Question 4 (20 marks)

A Gas Metal Arc Welding (GMAC) operation takes place on 15mm thick aluminum steel plate, producing a butt weld as shown below in Figure 4. As part of the process, a 3mm diameter aluminum electrode is used which also provides the filler metal for the welding operation. The weld geometry can be approximated as a trapezoid with 10 mm and 5 mm as the top and bottom dimensions, respectively. The width of the plates being welded is 40mm. If the voltage applied is 20 V at 120 A.

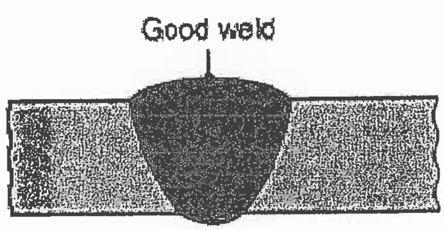

Figure 4 – x-sectional view of the weld.

a. Estimate the total energy (in KJ) required to create the weld based on the geometry of the weld given above. Assume that that weld material attains the melting temperature of the aluminum (use Table 2 below as needed). (5 marks)

   Assuming the efficiency of the welding operation is 90%, estimate the following:

b. The welding speed (m/s) (3 marks)
c. The deposition rate (mm^3/s) (3 marks)
d. Time to complete the weld (s) (3 marks)
e. Electrode feed rate (mm/s) (3 marks)
f. The cost of making this weld if the price of electricity is 15 cents per KWhour? (3 marks)

The area of a trapezoid is given as : – as shown below:

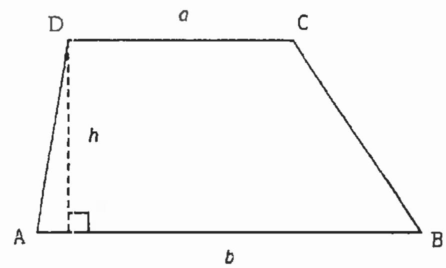

Table 2a - Data for solid materials (room temperature):

Material	Specific heat (kJ/kg°C)	Density (kg/m^3)	Thermal conductivity (W/m°C)
Sand	1.16	1500	0.6
Aluminum	0.90	2700	222.0
Nickel	0.44	8910	92.1
Magnesium	1.03	1740	154.0
Copper	0.38	8960	394.0
Iron	0.46	7870	75.4
Steel	0.434	7832	59.0

Table 2b - Data for liquid materials:

Material	Melting point (°C)	Density (kg/m^3)	Latent heat of solidification (kj/kg)	Thermal conductivity (W/m°C)	Specific heat (kJ/kg°C)	Viscosity (mPa-s)
Aluminum	660	2390	396	94.1	1.05	4.5
Nickel	1453	7900	297	84.1	0.73	4.1
Magnesium	650	1585	384	139.0	1.38	1.24
Copper	1083	7960	220	49.4	0.52	3.36
Iron	1540	7150	211	65.0	0.34	2.2

Material Property Tables (Steels)

Designation and Composition, %	Liquidus/ Solidus, °C	Hot Working: Usual Temp., °C	Flow Stress,[†] MPa: at °C	C	m	Work-ability[¶]	Cold Working: Flow stress,[‡] MPa: K	n	$\sigma_{0.2}$, MPa	TS, MPa	Elonga-tion, %	q RA, %	Annealing Temp.,[§] °C
Steels:													
1008 (0.08C), sheet		<1250	1000	100	0.1	A	600	0.25	180	320	40	70	850–900 (F)
1015 (0.15C), bar		<1250	800	150	0.1	A	620	0.18	300	450	35	70	850–900 (F)
			1000	120	0.1								
			1200	50	0.17								
1045 (0.45C)		<1150	800	180	0.07	A	950	0.12	410	700	22	45	790–870 (F)
			1000	120	0.13								
			1000	120	0.1	A			350	620	30	60	
~8620 (0.2C, 1Mn, 0.4Ni, 0.5Cr, 0.4Mo)													
D2 tool steel (1.5C, 12Cr, 1Mo)		900–1080	1000	190	0.13	B	1300	0.3					880 (F)
H13 tool steel (0.4C, 5Cr 1.5Mo, 1V)			1000	80	0.26	B							
302 SS (18Cr, 9Ni) (austenitic)	1420/1400	930–1200	1000	170	0.1	B	1300	0.3	250	600	55	65	1010–1120 (Q)
410 SS (13Cr) (martensitic)	1530/1480	870–1150	1000	140	0.08	C	960	0.1	280	520	30	65	650–800
Copper-Base Alloys:													
Cu (99.94%)	1083/1065	750–950	600	130 (48)	0.06 (0.17)	A	450	0.33	70	220	50	78	375–650
			900	41	0.2								
Cartridge brass (30Zn)	955/915	725–850	600	100	0.24	A	500	0.41	100	310	65	75	425–750
			800	48	0.15								
Muntz metal (40Zn)	905/900	625–800	600	38	0.3	A	800	0.5	120	380	45	70	425–600
			800	20	0.24								
Leaded brass (1Pb, 39Zn)	900/855	625–800	600	58	0.14	A	800	0.33	130	340	50	55	425–600
			800	14	0.20								
Phosphor bronze (5Sn)	1050/950		700	160	0.35	C	720	0.46	150	340	57		480–675
Aluminum bronze (5Al)	1060/1050	815–870				A			170	400	65		425–750

[*] Compiled from various sources; most flow stress data from T. Altan and F. W. Boulger, *Trans. ASME, Ser. B, J. Eng. Ind.* **95**:1009 (1973).

[†] Hot-working flow stress is for a strain of $\epsilon = 0.5$. To convert to 1000 psi, divide calculated stresses by 7.

[‡] Cold-working flow stress is for moderate strain rates, around $\dot{\epsilon} = 1\ s^{-1}$. To convert to 1000 psi, divide stresses by 7.

[§] Furnace cooling is indicated by *F*, quenching by Q.

[¶] Relative ratings, with A the best, corresponding to absence of cracking in hot rolling and forging.

Material Property Tables (Light Metals, Low Melting Metals and high Temperature Alloys)

		Hot Working					Cold Working						
Designation and Composition, %	Liquidus/ Solidus, °C	Usual Temp., °C	Flow Stress,[b] MPa at °C	C	m	Workability[f]	Flow stress[c] MPa K	n	$\sigma_{0.2}$, MPa	TS,[c] MPa	Elongation,[d] %	q RA, %	Annealing Temp.,[e] °C
Light Metals:													
1100 Al (99%)	657/643	250–550	300	60	0.08	A	140	0.25	35	90	35		340
			500	14	0.22								
~3003 Al (1Mn)	649/648	290–540	400	35	0.13	A			40	110	30		370
~2017 Al (3.5Cu, 0.5Mg, 0.5Mn)	635/510	260–480	400	90	0.12	B	380	0.15	70	180	20		415 (F)
			500	36	0.12								
5052 Al(2.5Mg)	650/590	260–510	480	35	0.13	A	210	0.13	90	190	25		340
6061-0(1Mg, 0.6Si, 0.3Cu)	652/582	300–550	400	50	0.16	A	220	0.16	55	125	25	65	415 (F)
			500	37	0.17								
6061-T6	NA[g]	NA	NA	NA	NA	NA	450	0.03	275	310	8	45	
~7075 Al(6Zn, 2Mg, 1Cu)	640/475	260–455	450	40	0.13	B	400	0.17	100	230	16		415
Low-Melting Metals:													
Sn (99.8%)	232	100–200				A				15	45	100	150
Pb (99.7%)	327	20–200	100	10	0.1	A				12	35	100	20–200
Zn (0.08% Pb)	417	120–275	75	260	0.1	A				130/170	65/50		100
			225	40	0.1								
High-Temperature Alloys:													
Ni (99.4Ni + Co)	1446/1435	650–1250				A			140	440	45	65	650–760
Hastelloy X (47Ni, 9Mo, 22Cr, 18Fe, 1.5Co, 0.6W)	1290	980–1200	1150~	140	0.2	C			360	770	42		1175
Ti (99%)	1660	750–1000	600	200	0.11	C			480	620	20		590–730
			900	38	0.25	A							
Ti 6Al 4V	1660/1600	790–1000	600	550	0.08	C			900	950	12		700–825
			900	140	0.4	A							
Zirconium	1852	600–1000	900	50	0.25	A			210	340	35		500–800
Uranium (99.8%)	1132	~700	700	110	0.1				150	380	4	10	

[a] Empty spaces indicate unavailability of data. Compiled from various sources; most flow stress data from T. Altan and F. W. Boulger, *Trans. ASME, Ser. B, J. Eng. Ind.* **95**:1009 (1973).

[b] Hot-working flow stress is for a strain of $\epsilon = 0.5$. To convert to 1000 psi, divide calculated stresses by 7.

[c] Cold-working flow stress is for moderate strain rates, around $\dot{\epsilon} = 1\ s^{-1}$. To convert to 1000 psi, divide stresses by 7.

[d] Where two values are given the first is longitudinal, the second transverse.

[e] Furnace cooling is indicated by F.

[f] Relative ratings, with A the best, corresponding to absence of cracking in hot rolling and forging.

[g] NA Not applicable to the -T6 temper.

Formulae Sheet

1) Casting

$Energy = \rho V\left[C_{solid}(T_{melt} - T_{initial}) + \Delta H + C_{liquid}(T_{pour} - T_{melt})\right]$		
$Q = A_1 v_1 = A_2 v_2$	$Re = \frac{vD\rho}{\eta}$	$t = C\left(\frac{V}{A}\right)^n$
$\square_0 + \frac{\square_0^2}{2} + \square h_0 = \square_1 + \frac{\square_1^2}{2} + \square h_1 + \square$		

2) Mechanical Behaviour of materials

$\sigma_{eng} = \frac{F}{A_o}$	$e = \frac{\Delta l}{l_o}$	$\sigma = \frac{F}{A_i}$	$\varepsilon = ln\left(\frac{l_i}{l_o}\right)$
$\sigma = \sigma_{eng}(1+e)$	$\varepsilon = \ln(1+e)$	$\dot{\varepsilon} = \frac{v}{l} = \frac{v}{h}$	$\sigma = K\varepsilon^n$
$\sigma = C\dot{\varepsilon}^m$	$\Delta T = \frac{u_{Total}}{\rho C}$	$\bar{Y} = \frac{K\varepsilon^n}{n+1}$	$T_h = \frac{T}{T_{mp}}(K)$
$\sigma_{max} - \sigma_{min} = Y$	$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2Y^2$		

3) Bulk Deformation

Forging

$P = Y' e^{\left[\frac{2\mu}{h}(a-x)\right]}$	$P_{avg} \simeq Y'\left(1 + \frac{\mu a}{h}\right)$	$P = Y'\left(1 + \frac{a-x}{h}\right)$
$P_{avg} = Y'\left(1 + \frac{a}{2h}\right)$	$P = Y e^{2\mu \frac{(r-x)}{h}}$	$P_{avg} \cong Y\left(1 + \frac{2\mu r}{3h}\right)$
$P = Y\left(1 + \frac{r-x}{h}\right)$	$P_{avg} \cong Y\left(1 + \frac{r}{3h}\right)$	$F = P_{avg} Area$
Rolling		
$L = \sqrt{R\Delta h}$	$\tan(\alpha) = \sqrt{\frac{\Delta h}{R}}$	$\mu \geq \tan(\alpha)$
$\Delta h_{max} = \mu^2 R$	$h_{min} = \frac{C\mu R}{E'}(\sigma_{flow} - \sigma_t)$	$E' = \frac{E}{1 - \upsilon^2}$
$\dot{\varepsilon} = \frac{V_r}{L} ln\left(\frac{h_f}{h_o}\right)$	$\bar{Y} = \frac{K}{\varepsilon_1 - \varepsilon_0}\left[\frac{\varepsilon_1^{n+1} - \varepsilon_0^{n+1}}{n+1}\right]$	$h_{avg} = \frac{h_o + h_f}{2}$
$p_{avg} \cong 1.15\bar{Y}_{flow}\left(1 + \frac{\mu L}{2h_{avg}}\right)$	$p_{avg} \cong 1.15\bar{Y}_{flow}\left(1 + \frac{L}{4h_{avg}}\right)$	
$T = \frac{F_r L}{2}$	$\omega = 2\pi N$	$Power\ (P) = \omega T$

4) Sheet metal forming

Shearing

$F_{max} = 0.7(UTS)tL$		
Bending		
$F_{max} = k\frac{(UTS)Lt^2}{W}$	$\frac{R_i}{R_f} = 4\left(\frac{R_i Y}{Et}\right)^3 - 3\left(\frac{R_i Y}{Et}\right) + 1$	$e_o = \frac{1}{\left(\frac{2R}{t}\right) + 1} \leq e_u$
$Minimum\ \frac{R}{t} = \frac{50}{r} - 1$		
Drawing		
$F_{max} = \pi D_p t_o (UTS)\left(\frac{D_o}{D_p} - 0.7\right)$	$DR = \frac{D_o}{D_p}$	$LDR = \frac{D_o(max)}{D_p}$
Anisotropy		
$R = \frac{\varepsilon_w}{\varepsilon_t}$	$\bar{R} = \frac{R_0 + 2R_{45} + R_{90}}{4}$	$\Delta R = \frac{R_0 - 2R_{45} + R_{90}}{2}$

5) Powder metallurgy, ceramics and polymers

$p_x = p_o e^{-4\mu kx/D}$	$V_{sint} = V_{green}\left(1 - \frac{\Delta L}{L_o}\right)^3$	$L_{sint} = L_{green}\left(1 - \frac{\Delta L}{L_o}\right)$
Polymer Extrusion		
$Q = Q_d - Q_p$	$Q_d = \frac{\pi^2 HD^2 N sin\theta cos\theta}{2}$	$Q_p = \frac{p\pi DH^3 sin^2\theta}{12\eta l}$
$Q_{die} = Kp$	$K = \frac{\pi D_d^4}{128\eta l_d}$	$P_{ext} = \rho QC(T - T_{RT}) + \rho QH + \Delta PQ$

6) Welding and Joining

$\frac{H}{l} = e\frac{VI}{v}$	$v = e\frac{VI}{uA}$	$H = I^2 Rt$