National Exams December 2011
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. Candidates are allowed to bring ONE aid sheet 8.5" x 11" hand-written on both sides containing notes and formulae.
4. All questions should be answered or attempted.
5. They are four questions and they are all of equal value.
6. Some common formulae are given at the end of the examination as well as material property tables.

Question 1 (20 marks)

a. Describe two differences between sheet metal forming and bulk deformation processes? (2 marks)

b. Why does increasing the normal anisotropy of a material improve its deep drawability? (2 marks)

c. Using brief sentences and sketches where appropriate, define and differentiate between: yield stress and flow stress (2 marks)

d. A cylinder with a height (h) to radius (h/a) ratio of 3 solidifies in five minutes in a sand-mold. Calculate the solidification time if the (h/a) ratio was changed to unity? Note: the top and bottom of the cylinder should be included in your analysis (2 marks). Hint: Use Chvorinov's rule with n = 2.

e. Sketch a graph showing the effect of compaction pressure on the porosity and strength of a green powder metallurgy compact during pressing (2 marks)

f. There are four different metals with given K, n and m values shown below at room temperature. What is the probable ranking sequence of them (lowest to highest) with respect to uniform elongation before necking? (2 marks)

Material	Strength parameter K (MPa)	Work hardening (n)	Strain rate sensitivity (m)
A	500	0.08	0.001
B	250	0.25	0.005
C	200	0.25	0.007
D	300	0.10	0.002

g. Explain for a given sheet thickness of material if springback would be greater for a larger or smaller bending radius. Explain your answer. (2 marks)

h. Make a sketch indicating the essential elements of Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW) indicating filler rod (base or coated), protective atmosphere, electrode etc (2 marks)

i. In plane strain rolling processes why is the factor 1.15 or $\frac{2}{\sqrt{3}}$ used as a multiplication factor to correct for the uniaxial yield stress? (2 marks)

j. Describe what occurs during sintering of a powder metallurgy component (2 marks)

Question 2 (20 marks)

You wish to bend a 2.1 mm thick piece of AISI 1045 steel to a final angle of 90 degrees. The steel has an elastic modulus, E = 210 GPa; The piece of metal is 1.3 m deep (into and out of the board) and has a length of 100 cm. The distance between the die shoulders is 45 mm. Determine:

a. The minimum punch radius to ensure necking does not occur (2 marks)

b. The minimum punch radius to ensure fracture does not occur (3 marks)

c. If using a 100 mm punch radius determine the radius of the part after it is bent and springback has occurred (5 marks)

d. Using the minimum punch radius from part a) determine if the material would plastically deform during the bending operation (5 marks)

e. Calculate the work done during this bending process by assuming the average engineering strain experienced by the material is 0.1. (5 marks)

Question 3 (20 marks)

Consider the room-temperature, open-die forging of a cylindrical billet of H13 tool steel at a platen speed of 0.56 m/min. The billet is 225 mm in diameter and 400 mm long. The product is 250 mm long. The platens are poorly lubricated, with a coefficient of friction equal to 0.4.

a. Determine the final dimensions (diameter) of the product after the forging operation. (1 mark)

b. Calculate the average pressure at the end of the deformation (5 marks)

c. Determine the power required to do this deformation in watts (10 marks)

d. Calculate the efficiency of the operation and sketch the pressure profile under the platen in contact with the billet indicating the portion of the pressure profile that is associated with deformation of the material and that associated with overcoming friction. (4 marks)

Question 4 (20 marks)

Consider the production of a multi-material (aluminum and steel) car frame by resistance welding of two sheets that are 3 mm thick each. The effective resistance of the multi-material weld can be assumed to be $4.1 \times 10^{-4}\ \Omega$ and the electrodes have a diameter of 10mm. Room temperature can be considered to be 20 °C. Determine the following:

a. Minimum energy required to create the weld assuming complete melting of the material under the electrodes. (5 marks)

b. If the efficiency of the process is 30% and the total time for welding is 5 sec, calculate the required current to do the weld. (5 marks)

c. If production rates increase to 35 welds/minute and the time to move (reposition) the welding apparatus between two welds is 1.5 s, calculate the current required. (5 marks)

d. If the cost of electricity is $0.09/kW-hr determine the cost of the electricity in an 8 hr day to make the welds. (Note 1 kW-hr = 3.6 MJ) (5 marks)

Table 1a - 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 1b - 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)

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

Material Property Tables (Steels)

Designation and Composition, %	Liquidus/ Solidus, °C	Hot Working: Usual Temp., °C	Hot Working: Flow Stress,† MPa at °C	Hot Working: Flow Stress,† MPa C	Hot Working: Flow Stress,† MPa m	Hot Working: Workability§	Cold Working: Flow stress,‡ MPa K	Cold Working: Flow stress,‡ MPa n	Cold Working: $\sigma_{0.2}$, MPa	Cold Working: TS, MPa	Cold Working: Elongation, %	Cold Working: 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)

Designation and Composition, %	Liquidus/ Solidus, °C	Usual Temp., °C (Hot Working)	Flow Stress,[b] MPa: at °C (Hot Working)	Flow Stress,[b] MPa: C (Hot Working)	Flow Stress,[b] MPa: m (Hot Working)	Workability[f]	Flow stress[c] MPa: K (Cold Working)	Flow stress[c] MPa: n (Cold Working)	$\sigma_{0.2}$, MPa (Cold Working)	TS,[c] MPa (Cold Working)	Elongation,[d] % (Cold Working)	RA,[g] %	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				190	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

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

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

$P = Y'e^{\left[\frac{2\mu}{h}(a-x)\right]}$	$P_{avg} \simeq Y'\left(1+\frac{\mu a}{h}\right)$	$P = Y'\left(1+\frac{a-x}{h}\right)$
$P_{avg} = Y'\left(1+\frac{a}{2h}\right)$	$P = Ye^{2\mu\frac{(r-x)}{h}}$	$P_{avg} \cong Y\left(1+\frac{2\mu r}{3h}\right)$
$P = Y\left(1+\frac{r-x}{h}\right)$	$P_{avg} \cong Y\left(1+\frac{r}{3h}\right)$	$F = P_{avg}Area$

Rolling

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

4) Sheet metal forming

Shearing

$F_{max} = 0.7(UTS)tL$		

Bending

$F_{max} = k\frac{(UTS)Lt^2}{W}$	$\frac{R_i}{R_f} = 4\left(\frac{R_iY}{Et}\right)^3 - 3\left(\frac{R_iY}{Et}\right) + 1$	$e_o = \frac{1}{\left(\frac{2R}{t}\right)+1} \leq e_u$
$Minimum\ \frac{R}{t} = \frac{50}{r} - 1$		

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

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