

Paper 3C2/P4B MATERIALS PROCESS MODELLING AND FAILURE ANALYSIS

Thursday 1 May 2003

Solutions

1 (i) Liquid metal embrittlement (one form of stress-corrosion cracking). LME requires tensile strain and a specific combination of liquid and host metals. The symptom is that in some combinations of liquid metal and solid (host) metal, the host metal suddenly fails by intergranular fracture. The molten metal (Zn) is able to run along inside cracks and then diffuse into the metal at the crack tip (generally diffusing along grain boundaries), reducing bond strengths at crack tip, so the process zone size falls to near zero and the metal becomes brittle.

Prevention: Nothing can be done to remove the tensile strain or to change the nature of the liquid metal, so we must change the host metal to something which is not susceptible to LME in contact with molten zinc. Or use a ceramic bath.

(ii) Hydrogen cracking. Free hydrogen (hydrogen atoms) enters the metal during electroplating, diffusing interstitially. Steel is embrittled and failure occurs by brittle fracture. Cracks usually start off intergranular, but may become transgranular later. Hydrogen can cause embrittlement by a range of mechanisms: bubbles of hydrogen gas under very high internal pressure forming inside the material, which assist crack growth by blowing the material apart; reducing cohesive strength of material at crack tip; promoting microslip at crack tips by locally reducing yield strength of metal.

Prevention: Two possible ways. (i) Use a lower-strength alloy. Steels with yield stress lower than about 700MPa are usually resistant to hydrogen cracking. However, this application may require a high-strength steel, so this may not be a viable route. (ii) Remove free hydrogen before bolts are put into service by baking (150-200°C for 1-2h).

(iii) Environmental Stress Cracking, ESC, also known as Environmentally Assisted Cracking, EAC. Requires a tensile stress and a specific combination of polymer and liquid or gas. The liquid or gas is often an organic material, and is not something which is thought of as being aggressive. Amorphous polymers are particularly susceptible. This is the danger: failure occurs with specific and unpredictable combinations of polymer and liquid/gas. The symptom is that the polymer fails at a stress well below its design stress. There may also be swelling of the polymer, or the polymer may become sticky (depolymerisation).

In this case, Noryl under tensile stress at the weld-line has been attacked by some substance in the aerosol spray (the propellant, as it turned out). The tensile stress has been provided by the welding: we are told that high stresses were needed to make good welds, so the polymer will have built-in stress and will still be under a high elastic stress after welding. Not all the plugs failed: we can predict that those which were not distorted before welding would have been relatively immune to ESC.

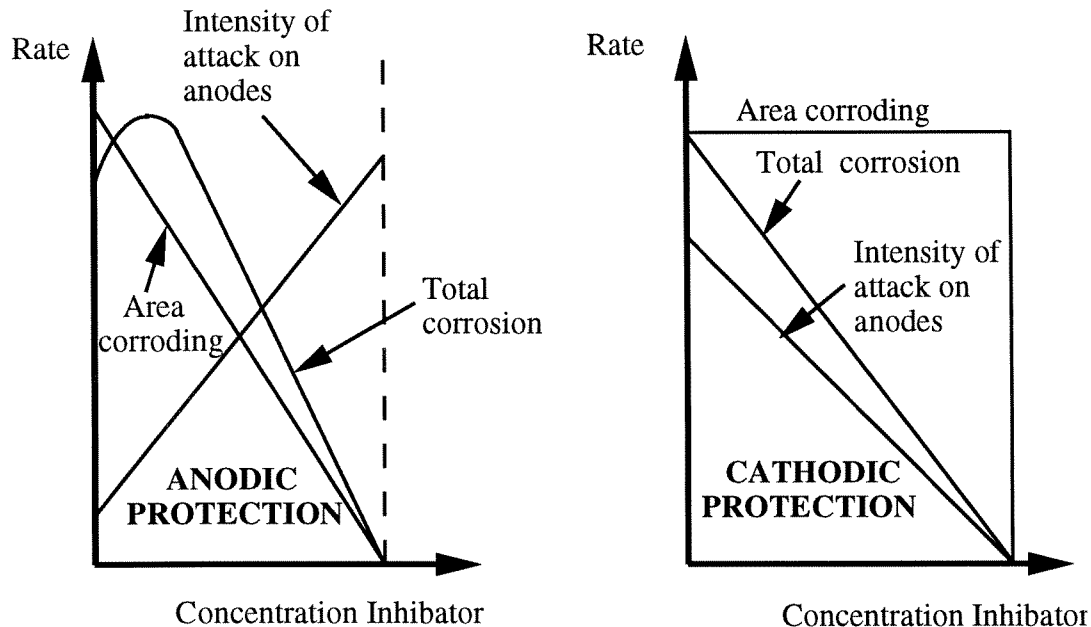
Prevention: Don't use the anti-static spray! But solvents may be around in service, so a safer solution would be to make sure that the susceptibility of the plugs to EAC is reduced by eliminating internal stresses. Reduce these by making sure that the parts are not distorted so that they can be welded without high stresses being applied.

(iv) Corrosion requires the presence of cathodic and anodic regions in the system; the dissolving of the anodic regions is what we see as corrosion. Anodic inhibition is being used here as the method of protecting the system against corrosion. This relies on protecting all the anodic regions (generally by precipitating some protective corrosion product). If, however, some areas are not protected then corrosion will be concentrated there, and rapid localised corrosion, often leading to pinhole failure, can be expected. If the system were steel (not specified here) the oxygen dissolved in the water is also

required for corrosion. The closed system loses nearly all its oxygen on heating, so corrosion rates fall. But adding extra water will give additional corrosion for a time. This will exacerbate the corrosion effects described above.

Prevention: Anodic inhibition requires the concentration of the protective additive to be kept above a specified minimum level. The system should have been topped up with additive at the same time as topping up with water.

An alternative prevention method is to use cathodic inhibition instead. This works by protecting the cathode areas, but is more robust because if they are not fully protected then all that happens is that slow corrosion takes place, spread over all the anodic areas. N.B. Diagrams were *not* required to score full marks.



2(a) Process models may be developed for any of the following reasons:

- explore new designs and process operating regimes, reducing the need for trials (e.g. modified runner/riser systems in developing castings; meeting hardness limits in new welding procedures)
- re-design of equipment (e.g. modification of extrusion dies for improved metal flow or more uniform heating of the metal)
- real-time control: physical understanding to improve control systems (e.g. balancing loads between stands in tandem rolling mill)
- process visualisation and development of new processes (e.g. friction stir welding)
- microstructure prediction and properties of product (e.g. Jominy end-quench hardness curves for new compositions; grain size distribution in superalloy jet engine forgings)
- interpreting failures, both during processing and in service (e.g. porosity in castings, cracking in extrusions, martensite formation in HAZ of steel welds, residual stresses and their contribution to fatigue or creep life)

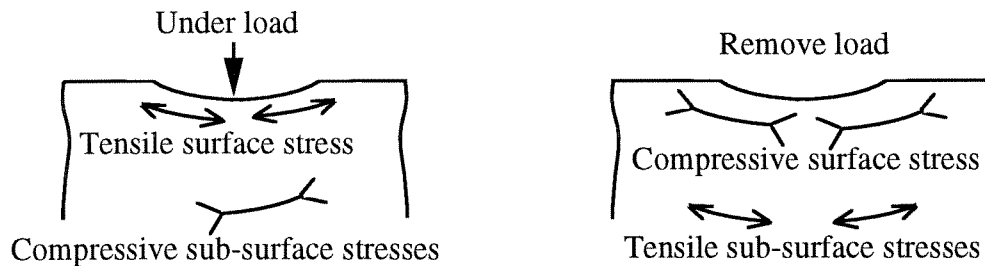
In brief, models contribute to design, control, failure analysis and innovation in manufacturing. Overall goals are cost reduction, enhanced productivity, lower scrap-rates, and greater process knowledge.

(b) The main advantages of using the finite element method rather than analytical methods are because they handle:

- complexity of geometric shape, boundary conditions (e.g. friction and heat transfer), and constitutive behaviour (e.g. flow stress dependence on temperature, strain-rate and strain)
- temperature-dependent material properties (hence more accurate) (e.g. thermal properties in quenching, such as Jominy bar test, or welding analysis).
- more than one material in the problem (e.g. casting and mould, melt and solid in a casting, metal billet and tools in hot working).

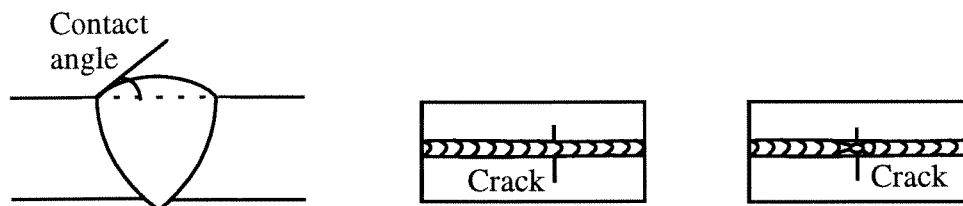
In addition, design/manufacture are becoming integrated electronically from CAD to dimensioning and stress analysis to process modelling and lifing. Numerical meshed methods fit naturally into this sequence of electronic data transfer.

(c) Shot-peening: Shoot lead shot or other particles at a surface. Model it as pressing a hard sphere into the surface. Under load there is plastic deformation, but also elastic stresses. The surface of the metal has been stretched and so is under tension; the material underneath is compressed. On removal of the load, the stresses reverse, so the surface goes into compression and there is sub-surface tension to balance this.



The compressed and work-hardened surface is resistant to crack nucleation, but cracks which grow through this layer can grow easily in the tensile sub-surface region. If the residual tension is too high, then cracks can nucleate there, run parallel to the surface, and can at worst cause the hard surface to lift off (spalling).

(d) Butt-welding: Joints have stress-concentrations arising from the profile of the surface, and from ripples or stop-start marks in the weld bead.



The stress concentrations can be reduced by machining the weld flat ('dressing'). The smaller the contact angle, the smaller the stress concentration. Dressing also removes ripples or stop-start marks.

Machining is generally done by grinding, which leaves grooves on the surface. These can act as stress concentrations, so it is important that these machining marks should be parallel to the direction along which the maximum stress is applied. The weld may be shot-peened to increase its strength.

3. (a) The main steps and assumptions made are:

(i) Assume axi-symmetric, force equilibrium conditions and analyse only half of the cross-section. Resolve forces on an individual element vertically and horizontally. Integrate with respect to distance and stress, applying boundary conditions to limits.

(ii) Principal stress axes are assumed along the symmetry axis and in plane, perpendicular to the symmetry axis. This is inexact because friction at the die surfaces will rotate the principal axes there. The error is small if the frictional stress $\ll Y$ and the die angle α is small. This is probably not the case here.

(iii) A yield criterion and flow rule have been assumed. (Tresca was used here but candidates are not expected to deduce this.) The main choice is between Tresca and von Mises, and in plane strain von Mises gives a 15% higher load for draw stress.

(iv) Friction; the dies are rough, so Coulomb or sticking friction may be assumed. The absence of a coefficient of friction in the result implies that Coulomb was not used, so probably this result was derived assuming sticking friction. Candidates should not make the mistake of supposing friction has been neglected – that would give the result $Y \ln(h_i/h_o)$ for the draw stress.

(v) Rigid, perfectly plastic behaviour: Elastic effects are neglected – this assumption is well justified provided the strains are \gg yield strain, which is likely. Work hardening is neglected, and this would have a substantial effect in Al alloys, but the real situation is complicated by the temperature dependence of yield stress, and the interaction between mechanical, thermal and microstructural behaviour.

(b) A valid solution is obtained by simply changing the boundary conditions to zero draw stress at the exit and compressive stress σ_d at the inlet. The extrusion force per unit depth is then simply $F = \sigma_d h_i$. To minimise $\sigma_d(\alpha)$ simply minimise;

$f(\alpha) = \tan(\alpha) + \cot(\alpha)$ i.e.;

$$\frac{d(\tan \alpha)}{d\alpha} = \tan^2 \alpha + 1 \quad \frac{d(\cot \alpha)}{d\alpha} = \cot^2 \alpha - 1$$

$$\frac{d[f(\alpha)]}{d\alpha} = \tan^2 \alpha + 1 + \cot^2 \alpha - 1 = \tan^2 \alpha + \cot^2 \alpha$$

$$\tan^2 \alpha + \cot^2 \alpha = 0, \text{ giving } \alpha_{\min} = \pi/4.$$

(c) For square dies there is likely to be a roughly triangular dead metal zone at the die. Since the analytical result was calculated using sticking friction, the dead metal could be considered as effectively part of the die and α_{\min} becomes a reasonable estimate of the effective die angle.

$$\begin{aligned} F = \sigma_d h_i &= 255 \text{ MPa} \times (1 + 1/2 + 1/2) \times \ln(25/10) \times 25 \text{ mm} \\ &= 12 \text{ MN/m. } (\sigma_d = 467 \text{ MPa}) \end{aligned}$$

Drawing requires $\sigma_d < Y$ to avoid failure of the sheet at the outlet. Here $\sigma_d > Y$.

(d) For simplicity, make the adiabatic assumption. Then $\Delta T = \sigma_d / \rho c_p = 180$ K. Hence the pre-heat temperature is $550 - 180^\circ\text{C} = 370^\circ\text{C}$. The assumptions are;

(i) that all the mechanical work goes to heat, neglecting increase in dislocation density, wear to tooling, etc.

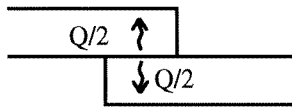
(ii) that all of the heat remains in the workpiece, so none is conducted to the tooling etc., and

(iii) that the heat is distributed uniformly throughout the emerging sheet.

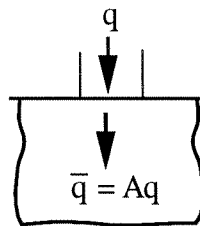
Assumption (iii) can be checked by considering thermal diffusion distance $x = \sqrt{a t}$. Here the relevant time scale is the transit time in the die. The die length is about 15 mm and the extrusion speed is 20mm/s, so $t \approx 1$ s. Hence $x \approx 7$ mm which is comparable to the sheet thickness, so this assumption is not too far off. However, at this low speed, significant heat transfer to the die may occur, so that the temperature rise is likely to be less than 173K in practice.

4. (a)

Problem;



Model as;



Power absorbed at interface = AQ

Power absorbed by each strip = $\frac{AQ}{2}$

Absorbed Power density = $\frac{(AQ/2)}{\pi r_B^2} = \bar{q} = Aq$

(b) Expressions for v^* , q^* , z^* , τ and $T_p - T_0$ are given in the question;

$$q^* = \frac{AQ}{r_B \lambda (T_p - T_0)}, \quad v^* = \frac{v r_B}{a} \quad \text{and} \quad z^* = \frac{z}{r_B}$$

$$T_p - T_0 = \frac{2 \bar{q} \sqrt{a \tau}}{\lambda \sqrt{\pi} \left(1 + \frac{z \sqrt{\pi}}{2 \sqrt{a \tau}} \right)} \quad \tau = \frac{2 r_B}{v}$$

$$a\tau = \frac{2ar_B}{v} = 2 r_B^2 \left(\frac{a}{v r_B} \right) = \frac{2r_B^2}{v^*} \quad \sqrt{a\tau} = \frac{\sqrt{2} r_B}{\sqrt{v^*}}$$

$$T_p - T_0 = \frac{\frac{AQ/\pi r_B^2}{\sqrt{\pi} \lambda} \frac{\sqrt{2}}{\sqrt{v^*}} r_B}{1 + \frac{\sqrt{\pi}}{2} z \frac{\sqrt{v^*}}{\sqrt{2} r_B}}$$

Rearrange into form of q^* ;

$$\Rightarrow q^* = \frac{AQ}{r_B \lambda (T_p - T_0)} = \frac{\pi^{3/2}}{\sqrt{2}} \sqrt{v^*} \left(1 + \frac{\sqrt{\pi}}{2\sqrt{2}} \frac{z}{r_B} \sqrt{v^*} \right)$$

$$\Rightarrow q^* = \frac{\pi^{3/2}}{\sqrt{2}} \sqrt{v^*} \left(1 + \sqrt{\frac{\pi}{8}} z^* \sqrt{v^*} \right)$$

$$(q^*)_{z=0} = \frac{\pi^{3/2}}{\sqrt{2}} \sqrt{v^*} \quad (\text{i.e. put } z = 0)$$

$$\frac{(q^*)_z}{(q^*)_{z=0}} = \left(1 + \sqrt{\frac{\pi}{8}} z^* \sqrt{v^*} \right) = \frac{(T_p - T_0)_{z=0}}{(T_p - T_0)_z}$$

(c) Want z and z^* $q^* = \frac{AQ}{r_B \lambda (T_p - T_0)}$

$$A = 0.1$$

$$Q = 120 \text{ W}$$

$$r_B = 2 \times 10^{-3} \text{ m}$$

$$\lambda = 0.145 \text{ W/m.K}$$

$$T_p - T_0 = T_m - T_0 = 250 - 20 = 230 \text{ K}$$

For melt depth $q^* = \frac{0.1 \times 120}{2 \times 10^{-3} \times 0.145 \times 230} = 180$

$$v^* = \frac{v r_B}{a}$$

$$v = 0.08 \text{ m/s}$$

$$a = 8.2 \times 10^{-8} \text{ m}^2/\text{s}$$

$$v^* = 1951 \text{ m/s}$$

Hence $180 = \frac{\pi^{3/2}}{\sqrt{2}} \sqrt{1951} \left(1 + \sqrt{\frac{\pi}{8}} z^* \sqrt{1951} \right)$

$$1 + \sqrt{\frac{\pi}{8}} z^* \sqrt{1951} = 1.035$$

Therefore $z^* = 8.94 \times 10^{-4} \text{ m}$

$$z_{\max} = z^* r_B = 1.79 \mu\text{m}$$

$$\frac{(T_p - T_0)_{z=0}}{(T_p - T_0)_z} = 1 + \sqrt{\frac{\pi}{8}} z^* \sqrt{v^*} = 1.035$$

$$\Rightarrow (T_p - T_0)_{z=0} = 1.035 \times (250 - 20)$$

$$\Rightarrow T_p \text{ at interface} = 258^\circ\text{C}$$

(d) Use result from part (b); $\frac{(T_p - T_0)_{z=0}}{(T_p - T_0)_z} = 1 + \sqrt{\frac{\pi}{8}} z^* \sqrt{v^*}$

$$(z^*)_{\text{HAZ}} = \frac{z}{r_B} = \frac{220 \mu\text{m}}{2 \text{ mm}} = 0.11$$

$$T_p - T_0 = 258 - 20 = 238^\circ\text{C}$$

$$(T_p - T_0)_z = \frac{238}{1 + \sqrt{\frac{\pi}{8}} 0.11 \sqrt{1951}} \approx 59$$

$$\Rightarrow T_p \approx 79^\circ\text{C}$$

T_p is therefore close to T_g .

The drawn sheet will have an aligned molecular structure. T_p above T_g will allow some relaxation, giving contrast when viewed under polarised light.