ECE414/514
Electronics Packaging
Fall 2012 Lecture 15

Reliability Failure Mechanisms:
fracture mechanics, fatigue, electromigration & popcorning

James E. Morris

Dept of Electrical & Computer Engineering

Portland State University

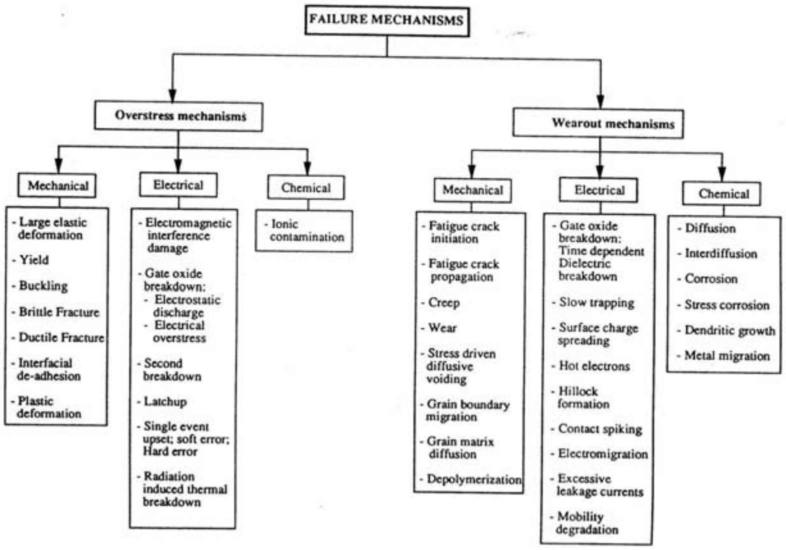
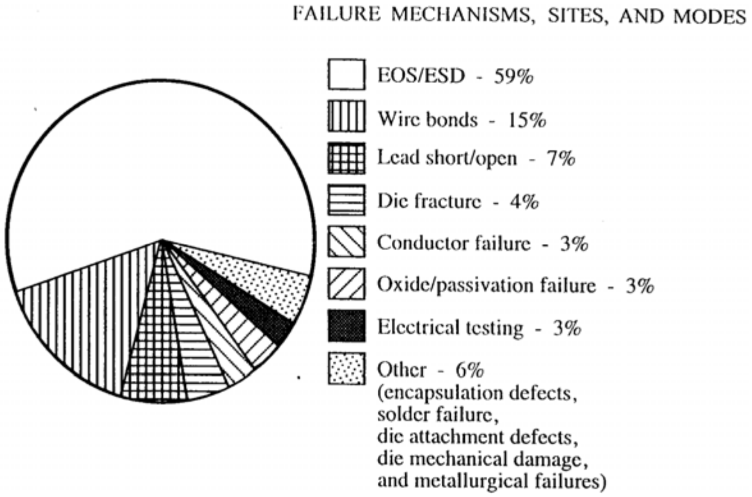
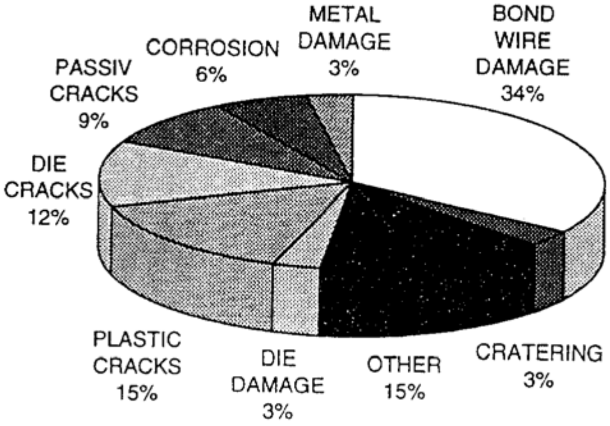


Figure 2.1 *Classification of failure mechanisms*

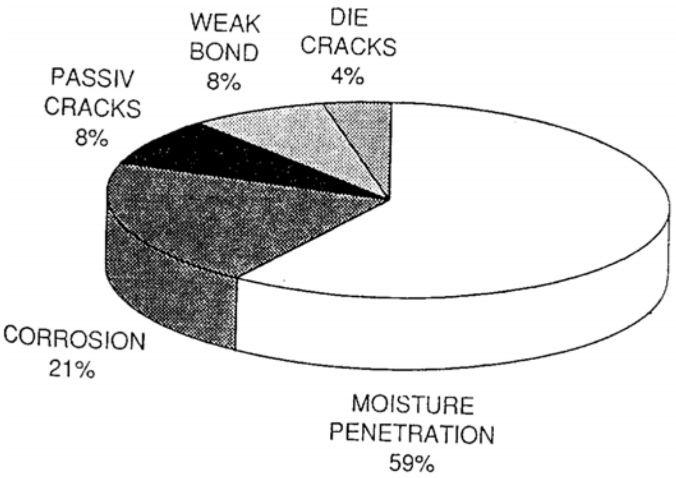
Distribution of Failures: Commercial integrated circuits (PEMs)



Temperature Cycle Failures

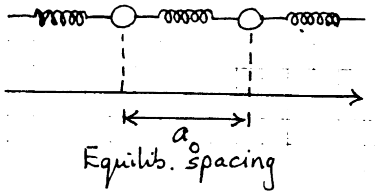


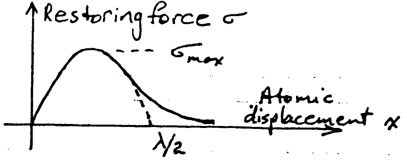
HAST Failures:1988-1994



Ideal/Theoretical Fracture Strength

Consider inter-atomic forces





Up to σ_{max} (and a little beyond)
approximate by $\sigma = \sigma_{max} \sin\left(\frac{2\pi x}{\lambda}\right)$

For small increments x :

Crystal strain $= \frac{dx}{a_0}$ & in the elastic region $E =$ stress/strain $= \frac{d\sigma}{dx/a_0}$
(Young's modulus)

$$\therefore \frac{d\sigma}{dx} = \frac{E}{a_0} = \sigma_{max} \cos\left(\frac{2\pi x}{\lambda}\right) \times \frac{2\pi}{\lambda} \approx \frac{2\pi}{\lambda}\sigma_{max} \quad (\text{for } x \ll \lambda)$$

$$\therefore \sigma_{max} = \frac{\lambda E}{2\pi a_0} \approx \frac{E}{2\pi} \quad \text{if } \lambda \sim a_0$$

σ_{max} corresponds to the point where the interatomic forces would yield, i.e. the material should break at about $\sigma_{max} = E/10$

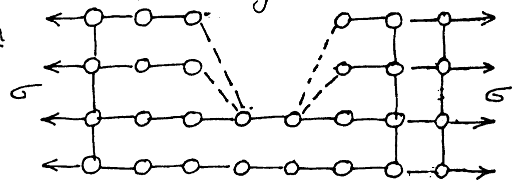
In practice: σ_f (measured) $\sim E/10^4$

(But very small samples i.e. thin films or whiskers can reach $\sigma_f \sim E/15$ or so.)

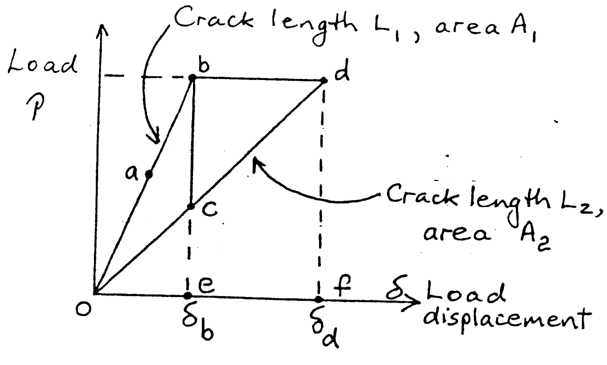
POSTULATE: Small flaws or micro-cracks.

(Statistically less likely to occur in a very small sample, hence size effect.) → Thin fibers stronger than thick rods.)

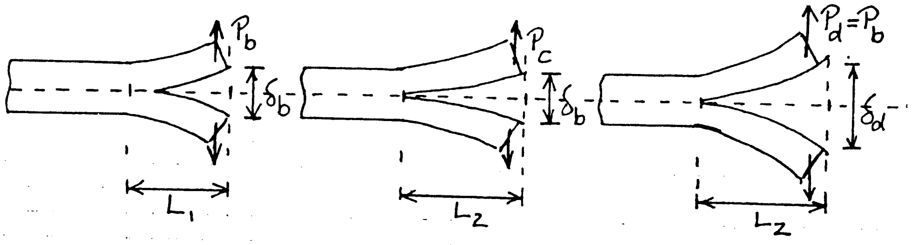
Stress concentration



Crack Mechanics



(Perpendicular sample thickness is t;
$\therefore A_1 = tL_1$
$A_2 = tL_2$)



Ob — elastic relationship for small crack L_1

Od — " " " large " L_2

When crack grows $L_1 \rightarrow L_2$, elastic curve shifts $b \rightarrow c$

if crack propagation $L_1 \rightarrow L_2$ at constant displacement δ_b

(or $b \rightarrow d$ if at constant load $P_b = P_d$)

Work is done to open crack:

For constant displacement
$b \rightarrow c$

Initial stored energy at b = $P\delta_b$ = area Obe

Final stored energy $\Longrightarrow$ Area Oce

∴ Work to open crack $\Longrightarrow$ Area(Obe - Oce) = Area Obc

Supplied from internal stored energy.

Reduced stored energy

For constant Load
$b \rightarrow d$

Area Odf = Oce from storage
+ ecdf from work.

Area (Obe + bdfe − Odf) = Obd

Represents external work P × distance

= Obc from internal storage
+ bdc from external work.

Energy absorbed by growth

i.e. Work = $R(A_2 - A_1)$ where R = fracture toughness

= $R\,t\,(L_2 - L_1)$

∴ $R \Longrightarrow \dfrac{\text{Area Obc}}{A_2 - A_1}$ $\qquad$ $\dfrac{\text{Area Obd}}{A_2 - A_1}$

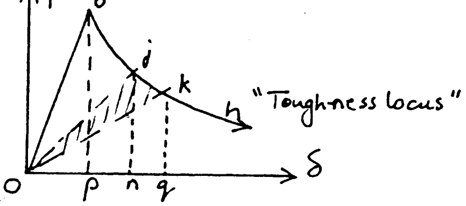
(greater, representing external work done)

For incremental crack growth $L_2 = L_1 + \Delta L$

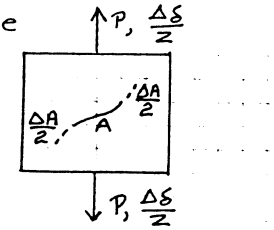
& for large P, the difference (Area bdc) $\longrightarrow 0$

bd → 0
bc → 0

In practice, crack growth



ENERGY BALANCE for general case



External work $= P\Delta\delta$

Crack growth absorbs energy $= R\,\Delta A$

Strain energy Λ changes by $\Delta\Lambda$

Strain energy at j is area $Ojn = \frac{1}{2}P\delta$

$\therefore\ \Delta\Lambda = \frac{1}{2}\Delta(P\delta)$

$\therefore$ External work $P\Delta\delta = \underset{\text{Change in internal strain energy}}{\Delta\Lambda} + \underset{\text{Crack growth takes energy.}}{R\,\Delta A}$

$$\therefore\quad P\Delta\delta = \tfrac{1}{2}\Delta(P\delta) + R\,\Delta A$$

$$= \tfrac{1}{2}P.\Delta\delta + \tfrac{1}{2}\delta.\Delta P + R\,\Delta A$$

ie. $$P.\Delta\delta - \delta.\Delta P = 2R.\Delta A$$

$$\frac{1}{P}\frac{\Delta\delta}{\Delta A} - \frac{\delta}{P^2}\frac{\Delta P}{\Delta A} = \frac{2R}{P^2} \quad \& \quad \frac{P}{\delta} = \text{“stiffness”}$$

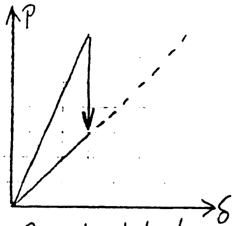
$$\frac{d}{dA}\left(\frac{\delta}{P}\right) = \frac{2R}{P^2} \longrightarrow P^2_{crack} = \frac{2R}{\frac{d}{dA}(\delta/P)}$$

L1

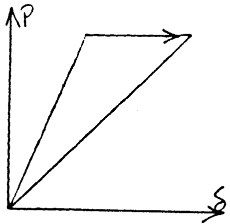
4.24

Note on notation: Using R fracture toughness here.

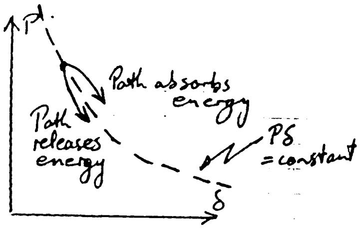
Commonly $R \xrightarrow[\text{written}]{} G_c$ "critical strain energy release rate"



Constant displacement
Final energy < Initial
∴ "released" by crack propagation

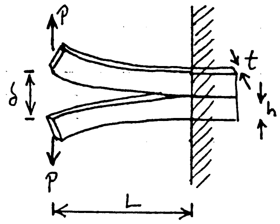


Constant Load
Final Energy > Initial
ie ~~work~~ absorbed by crack propagation



∴ energy "release" not general

Case 1: Thin beam



For cantilever beam, deflection $\frac{\delta}{2} = \frac{PL^3}{3EI}$

where $I = th^3/12$

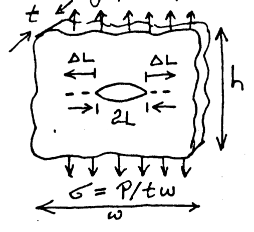
so $\frac{\delta}{P} = \frac{2}{3}\frac{L^3}{EI}$

& $dA = t\,dL$

so $\frac{d}{dA}\left(\frac{\delta}{P}\right) = \frac{1}{t}\frac{d}{dL}\left(\frac{2}{3}\frac{L^3}{EI}\right) = \frac{2L^2}{EIt}$

$P^2_{crack} = REIt/L^2$

Case 2: "Griffith" problem: elliptical crack



Stiffness $P/\delta = \frac{Etw}{h\left(1 + 2\pi\frac{L^2}{hw}\right)}$ ← Young's modulus of "flawless" material

& $A = 2L.t \therefore dA = 2t.dL$

& $\frac{d}{dA}\left(\delta/P\right) = \frac{1}{2t}\,\frac{h4\pi L/hw}{Etw} = 2\pi\frac{L}{Et^2w^2}$

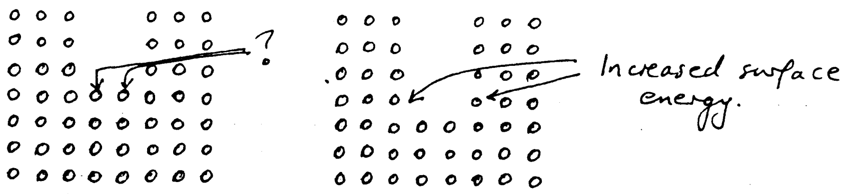
$\therefore P^2_{crack} = \frac{2R}{2\pi L/Et^2w^2} = \frac{ER}{\pi L}.(tw)^2$

& $\sigma^2_{crack} = ER/\pi L$

This is the Griffith equation for brittle fracture

Implies critical crack length, below which crack will NOT run for given stress.

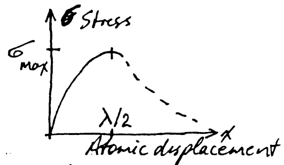
Physical Process: Microscopic Interpretation & Crack Tip Plasticity



Energy supplied to crack propagation

→ increase in surface energy

(broken bonds require energy input)



(see back)

λ just wavelength of approx. sine curve

"Expect" $\lambda \sim a_0$

$\therefore$ Work done to fracture

$$= \int_0^{\lambda/2} \sigma_{max} \sin\left(\frac{2\pi x}{\lambda}\right) dx$$

$$= \left[-\cos\frac{2\pi x}{\lambda}\right]_0^{\lambda/2} \sigma_{max}\frac{\lambda}{2\pi}$$

$$= \lambda\sigma_{max}/\pi$$

= Increase in energy of TWO surfaces

$= 2\gamma_s \leftarrow$ surface energy

i.e. $\sigma_{max} = \frac{2\pi}{\cancel{a_0}\lambda}\gamma_s$ relates σ_{max} to γ_s

Compare previously (without $\lambda \sim a_0$ approx:) $\sigma_{max} = \frac{\lambda}{2\pi a_0}E$ relates σ_{max} to E

(or $\sigma_{max} = E/2\pi$ if $\lambda = a_0$)

Suggests $E = \left(\frac{2\pi}{\lambda}\right)^2 a_0 \gamma_s$

Another commonly quoted result from $\sigma_{max} = \frac{2\pi\gamma_s}{\lambda}$ & $\sigma_{max} = \frac{\lambda E}{2\pi a_0}$ $\longrightarrow \sigma_{max} = \sqrt{\frac{E\gamma_s}{a_0}} \longrightarrow \sqrt{\frac{ER}{\pi L}}$

if $R = 2\gamma_s$

& $L = 2a_0/\pi$

4.23

Note: These variations all seem to be about the same as the first theoretical attempt

i.e. $\sigma_{max} \sim E/10$

which we already know is OK for very small (no crack) specimens, but too high for general use.

(a) Consider brittle materials (eg glass):

By measurement $R \sim \gamma_s$

So use the implied $R = 2\gamma_s$ above

& $\sigma_{crack} = \sqrt{\frac{ER}{\pi L}} \longrightarrow \sqrt{\frac{2E\gamma_s}{\pi L}} \approx \sqrt{\frac{E\gamma_s}{L}}$ Griffith Equation for brittle materials

(b) Consider ductile materials: $R \gg \gamma_s$

(typ $R \simeq 1000\gamma_s$)

Extra work goes into plastic deformation of crack tip zone

Brittle Cracking in Large/Practical Structures

There WILL be flaws! So fracture based on the existence of an initiating crack & $\sigma^2 \propto ER/L$

Young's Modulus ↑ ↑ Toughness ↑ Length of pre-existing crack

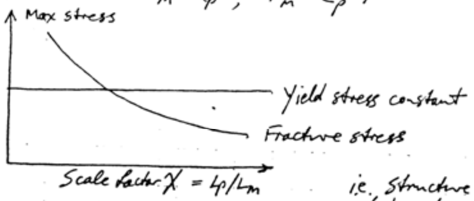
Consider large prototype structure & laboratory test model dimensions $L_p = \chi L_m$, L_m

$$\therefore \sigma_p^2 \propto E_p R_p / L_p \quad \& \quad \sigma_m^2 \propto E_m R_m / L_m$$

$$\& \quad \sigma_p^2 = (L_m / L_p)\, \sigma_m^2$$

$$\sigma_p = \chi^{-1/2} \sigma_m \qquad (\chi > 1)$$

(assumes $R_m = R_p$, $E_m = E_p$)



i.e. Structure which yields in laboratory model, may fracture in fullscale.

i.e. ductile material in lab may fail by fracture in large specimens

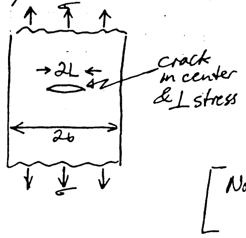
---

Fracture Mechanics

The ACTUAL fracture point is controlled by the stress field detail around the tip of the flaw/crack.

Define ① STRESS INTENSITY FACTOR = K

e.g.



$$K = \sigma\sqrt{\pi L} \cdot \sqrt{\frac{2b}{\pi L}\tan^{-1}(\pi L/2b)} \xrightarrow[\text{Small } L/b]{} \sigma\sqrt{\pi L}$$

&, define ② $K_c = \sqrt{ER}$

= CRITICAL STRESS INTENSITY FACTOR

[Note also ③ STRESS CONCENTRATION FACTOR (dimensionless) = $\frac{\text{local average stress at cross section change}}{\text{average stress}}$]

For small L/b, cracking occurs when $K \geq K_c$

$$\sigma\sqrt{\pi L} \geq \sqrt{ER}$$

for limiting case of small L/b

i.e. when $\sigma \geq \sqrt{\frac{ER}{\pi L}}$

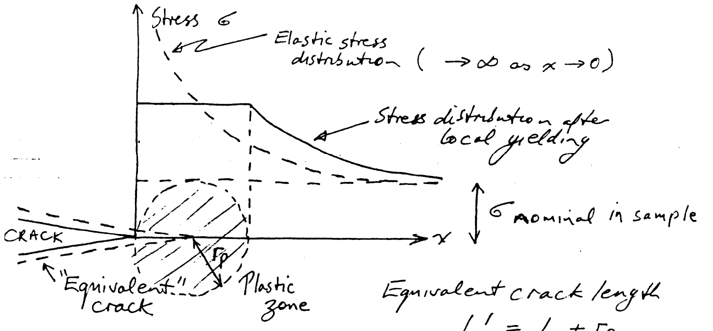
(see back)

In general, cracking/fracture occurs when

$$K = \sigma\sqrt{\pi L} \cdot Y \geq K_c = \sqrt{ER}$$

Y function of: (1) body shape/geometry (2) crack orientation & (3) type of loading

Plastic Zone Correction

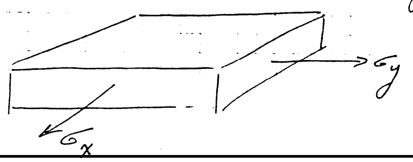


Equivalent crack length

$$L' = L + r_p$$

where $r_p = \frac{1}{2\pi}\left(\frac{K}{\sigma_y}\right)^2$ for "plane stress" case

or $r_p = \frac{1}{3} \cdot \frac{1}{2\pi}\left(\frac{K}{\sigma_y}\right)^2$ for "plane strain" case (typically plate of thickness $\geq 2r_p$ so ~0 strain in z direction.)



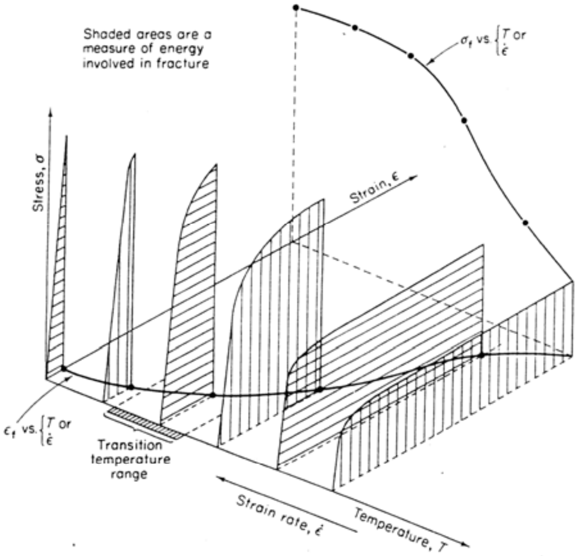
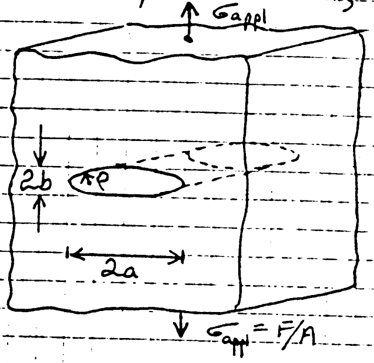


Figure 14-4 Relations between stress, strain, strain rate, and temperature in fracture. Brittle stress–strain curves transform to ductile curves at increasing temperature or decreasing strain rate (and vice versa) for most materials. Shaded areas under σ–ϵ curves are some measure of the energy involved in fracture. Change from brittle to ductile behavior takes place over a reasonably narrow span of temperature, called the transition temperature range; the position of this temperature range can vary with type of test piece and conditions of measurement.

Stress Concentration

Basic Case: elliptical hole, stress $\perp$ major axis



At end of major axis

$$\frac{\sigma_{max}}{\sigma_{appl}} = 1 + \frac{2a}{b}$$

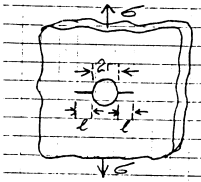
$$\xrightarrow[\rho = b^2/a]{} 1 + 2\sqrt{a/\rho}$$

radius of curvature at end of ellipse

$$\xrightarrow[\& \text{ for } a \gg \rho]{} 2\sqrt{a/\rho}$$

Hence stress concentration factor $k_t \equiv \dfrac{\sigma_{max}}{\sigma_{appl}} \approx 2\sqrt{a/\rho}$

Crack Initiation & Growth



For hole & crack

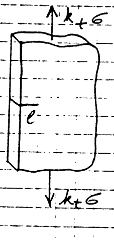
(a) If $r \ll \ell$ (long crack solution)

- Stress intensity factor $K_\ell \approx \sigma\sqrt{\pi a}$

where $a = r + \ell$ (as for static crack)

(b) If $r \gg \ell$

(limiting case is edge crack →

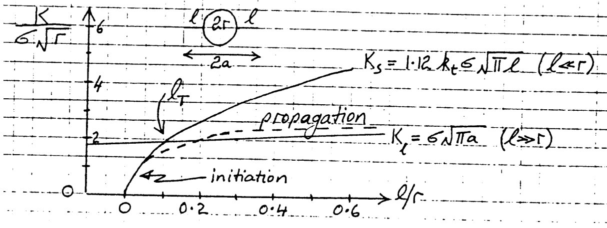


& Stress intensity factor $K_s = 1{\cdot}12\, k_t\, \sigma\sqrt{\pi\ell}$

Surface flaw correction factor

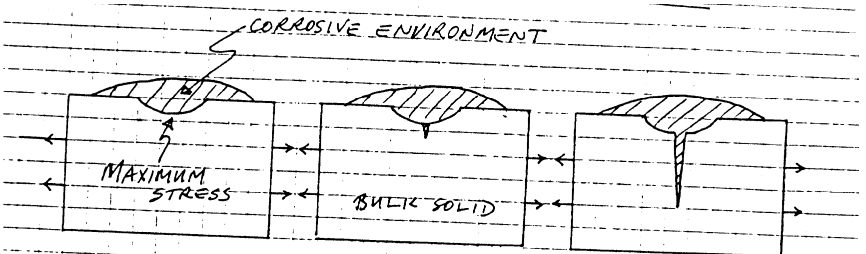
Stress concentration factor for hole in infinite plate

(short crack solution)



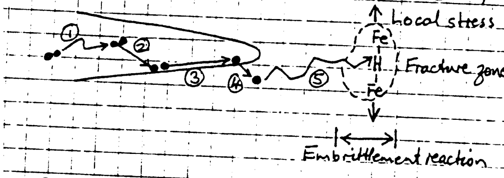
Use ℓ_T as the definition of crack initiation.

Stress-Corrosion Cracking



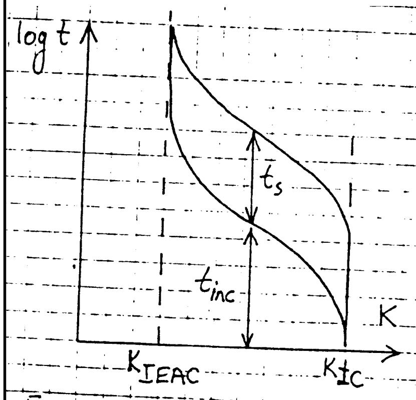
CRITICAL THRESHOLD STRESS-INTENSITY FACTOR FOR STRESS CORROSION CRACKING $K_{SCC} \sim (0.1 \Rightarrow 0.7) \times$ YIELD STRESS

HYDROGEN EMBRITTLEMENT



1. Gas phase transport
2. Physical absorption
3. Dissociation & chemical absorptio
4. Hydrogen entry
5. Diffusion

CORROSION : $M + H_2O \Rightarrow MO + H_2$ (H_2 source)



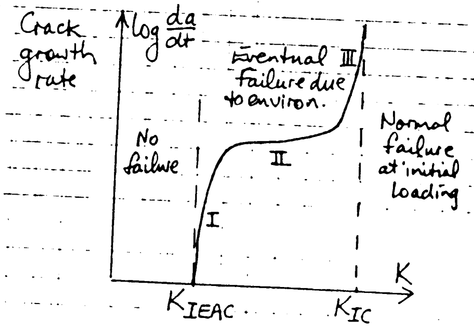
Environmentally assisted cracking stress threshold

t_{inc} crack incubation time

t_s steady state crack growth time

t_{tr} total time during transient crack growth

$t_T = t_{tr} + t_s + t_{inc}$ = time to failure



4

STRESS-CORROSION CRACK GROWTH & FAILURE PREDICTION

For multiple mechanisms — regions I, II & III

Effective rate determined by slowest

Writing $\frac{da}{dt} = \dot{a}$ $\qquad \frac{1}{\dot{a}_T} = \frac{1}{\dot{a}_I} + \frac{1}{\dot{a}_{II}} + \frac{1}{\dot{a}_{III}}$

$$\approx \frac{1}{\dot{a}_I} + \frac{1}{\dot{a}_{II}}$$

$$\therefore \dot{a}_T = \frac{\dot{a}_I \dot{a}_{II}}{\dot{a}_I + \dot{a}_{II}}$$

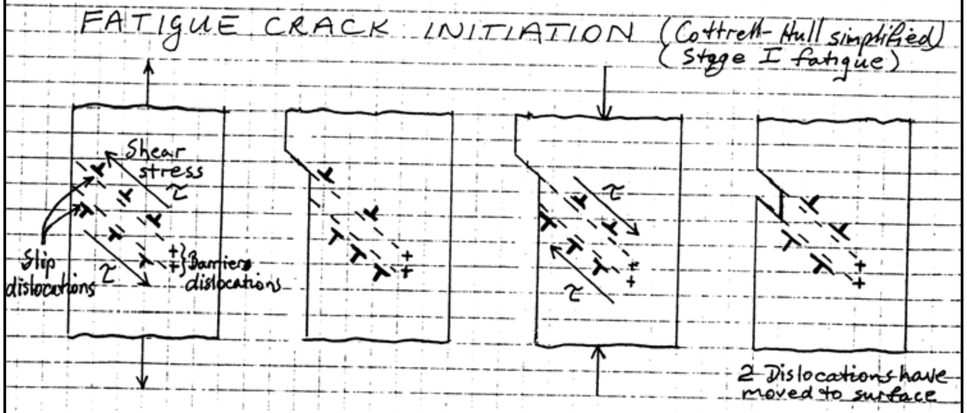
& steady state cracking time $t = \int_0^t dt = \int_{a_0}^{a_i} \frac{\dot{a}_I + \dot{a}_{II}}{\dot{a}_I \dot{a}_{II}} da$

where

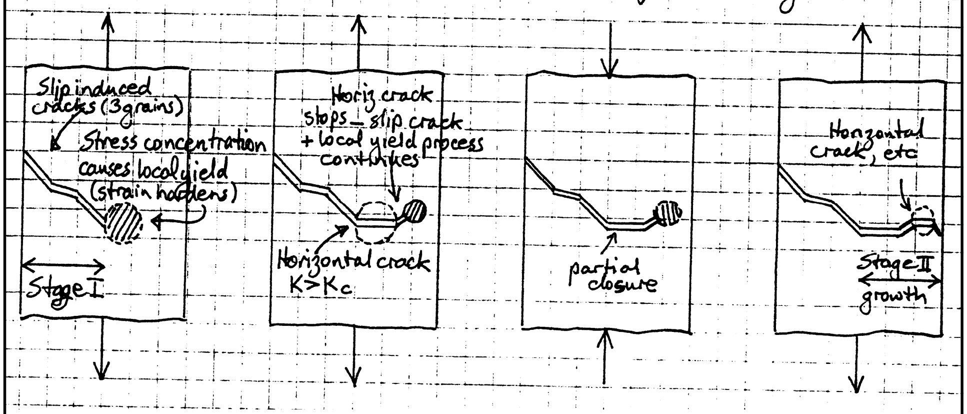
$$\dot{a}_I = C_1 e^{mK} \qquad C_1, m \text{ functions of } T, P$$

$$\dot{a}_{II} = C_2 P^n e^{-\Delta H/RT}$$

Fatigue Failure

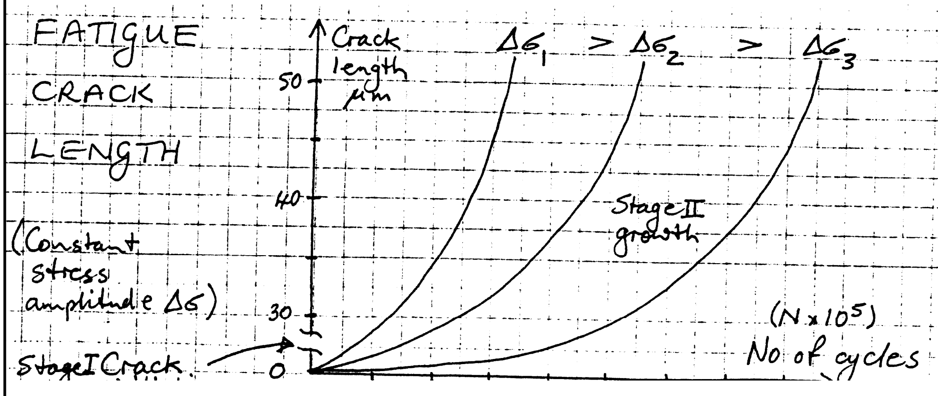


FATIGUE CRACK GROWTH (Stage II fatigue)

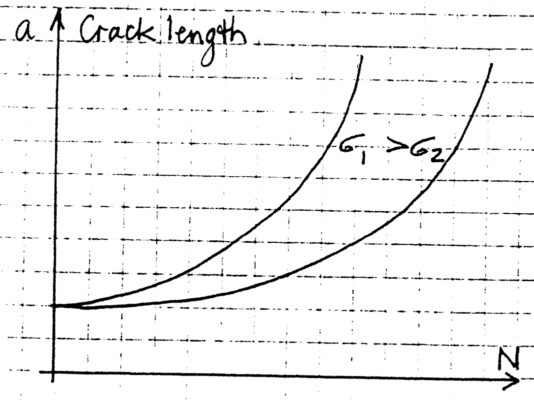


FATIGUE CRACK LENGTH

(Constant stress amplitude Δσ)



Fatigue Life



$$\frac{da}{dN} \propto \sigma^m a^n$$

$m \approx 2 - 7$

$n \approx 1 - 2$

Empirical relationship : $$\frac{da}{dN} = A \, \Delta K^m$$

where $\Delta K = Y \, \Delta\sigma \sqrt{a}$

$\uparrow$ geometrical correction

Failure lifetime $$N_f = \int dN = \int_{a_0}^{a_f} A^{-1} \, \Delta K^{-m} \, da$$

where a_0 = initial crack size, a_f = final crack size at failure

$$N_f = \int_{a_0}^{a_f} A^{-1} \, Y^{-m} \, \Delta\sigma^{-m} \, a^{-m/2} \, da$$

$$= \frac{1}{A \, Y^m \, \Delta\sigma^m} \left[\frac{a^{-\frac{m}{2}+1}}{-\frac{m}{2}+1} \right]_{a_0}^{a_f}$$

$$= \frac{2}{(m-2) A \, Y^m \Delta\sigma^m} \left\{ \frac{1}{a_0^{(m/2-)}} - \frac{1}{a_f^{(m/2-1)}} \right\}$$

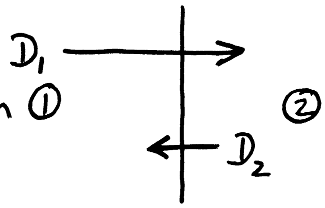
A, m material constants

for $m \neq 2$

Kirkendall Voids

Interface — dissimilar metals

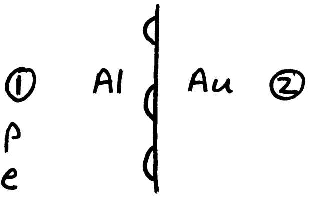
Metal 1:
High diffusion
coefficient
e.g. Al



Metal 2:
Lower diffusion
coefficient
e.g. Au

$D_1 > D_2$

Net effect:



Voids develop
on Metal 1 side

- * High resistance interface
- * Mechanically weakened
- * Diffusion constants increase rapidly with temperature.
  - ∴ Must keep temperatures low (temperature × time)

Also : Au/Cu → ductile intermetallics & voids
→ decreased bond strength

Electromigration

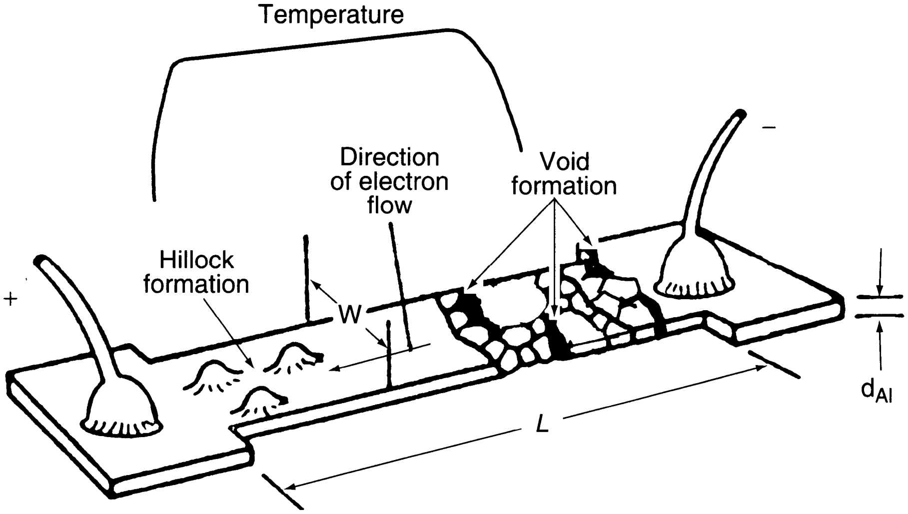
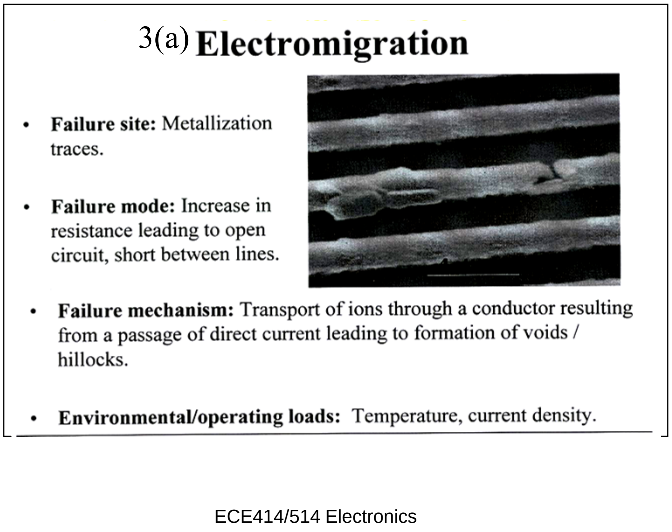


Fig. 5-15 Schematic model of damage in an interconnect subject to electromigration. Hillocks and voids develop in response to temperature gradients superimposed on the directed electron current flow.

Thermo- and Electrotransport Fail Mechanisms



3(a) **Electromigration**

- **Failure site:** Metallization traces.
- **Failure mode:** Increase in resistance leading to open circuit, short between lines.
- **Failure mechanism:** Transport of ions through a conductor resulting from a passage of direct current leading to formation of voids / hillocks.
- **Environmental/operating loads:** Temperature, current density.

Electromigration

- **Damage model**

$$T_f\,(hours) = \frac{Z_{met} * t_{met}}{\left(j_{met}\right)^{\varepsilon_{met}} * C * \exp\left(\dfrac{-H_{gb}}{K * T_{die}}\right)}$$

- **Package attributes**

  Metallization width, thickness.

- **Accelerated tests**

  High temperature operating life with bias.

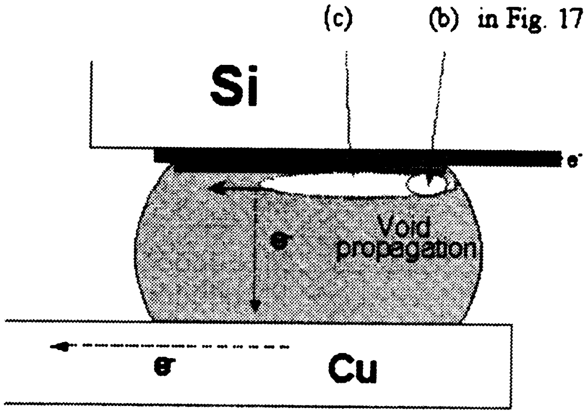


FIG. 19. Schematic diagram depicting the effect of void formation and propagation on the current entering the solder bump. While the current is being displaced to the front of the void, there is little change in resistance. Only when the void has propagated across the entire contact interface, the resistance will jump abruptly (Ref. 59).

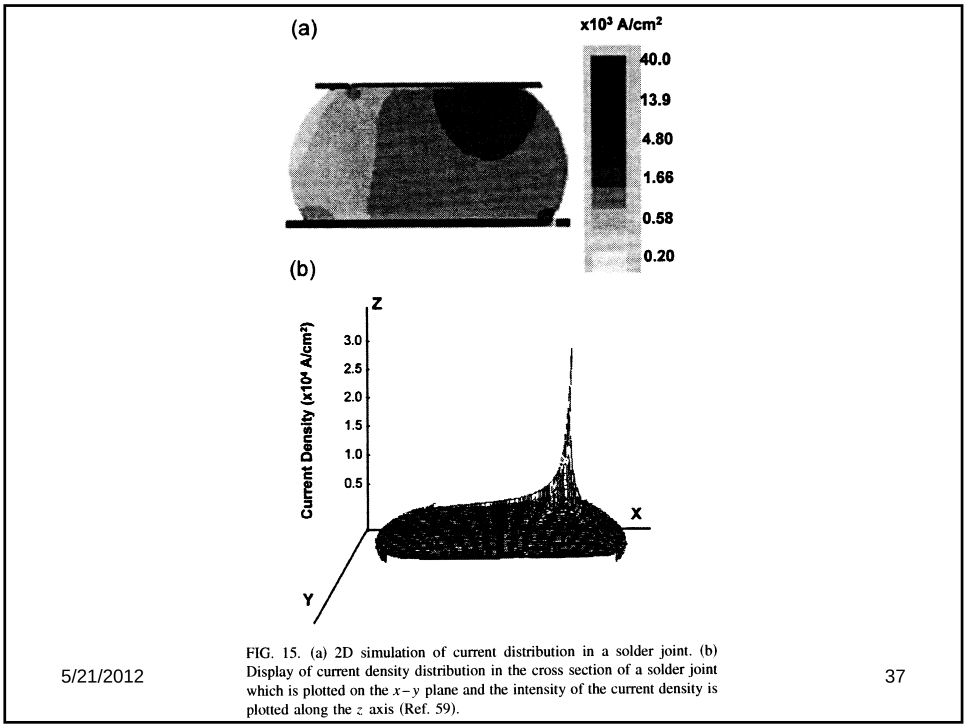
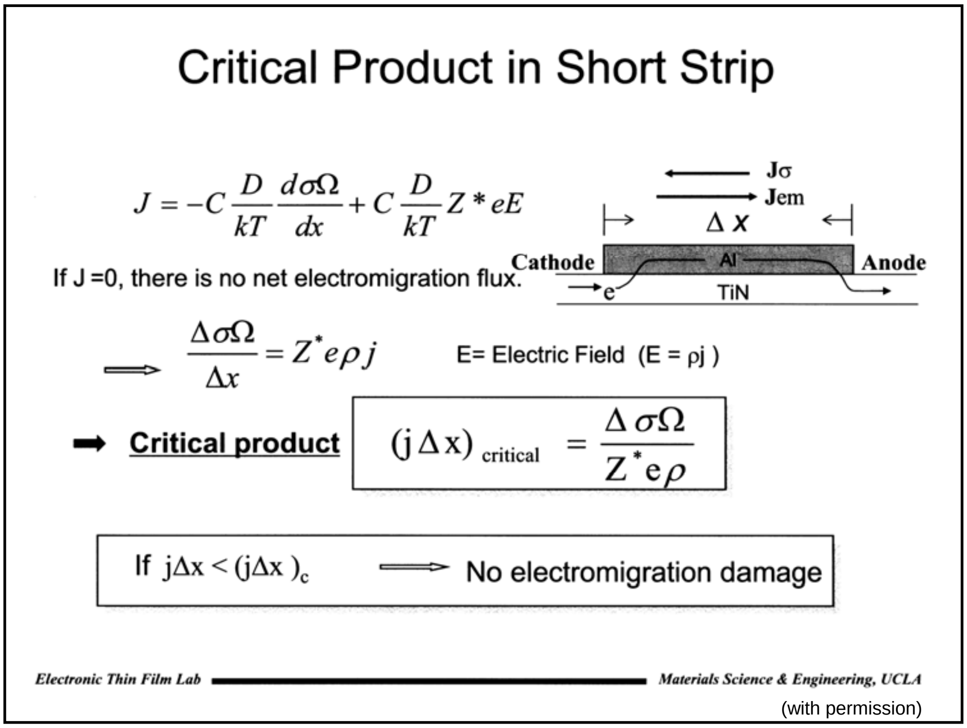


FIG. 15. (a) 2D simulation of current distribution in a solder joint. (b) Display of current density distribution in the cross section of a solder joint which is plotted on the $x-y$ plane and the intensity of the current density is plotted along the z axis (Ref. 59).



Critical Product in Short Strip

$$J = -C\frac{D}{kT}\frac{d\sigma\Omega}{dx} + C\frac{D}{kT}Z^*eE$$

If J =0, there is no net electromigration flux.

$$\Longrightarrow \frac{\Delta\sigma\Omega}{\Delta x} = Z^* e\rho j$$

E= Electric Field (E = ρj)

➡ **Critical product** $\boxed{(j\,\Delta x)_{\text{critical}} = \frac{\Delta\sigma\Omega}{Z^* e\rho}}$

$\boxed{\text{If } j\Delta x < (j\Delta x)_c \Longrightarrow \text{No electromigration damage}}$

Electronic Thin Film Lab — *Materials Science & Engineering, UCLA*

(with permission)

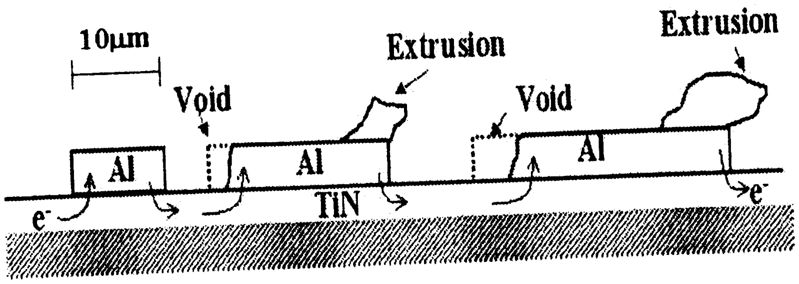
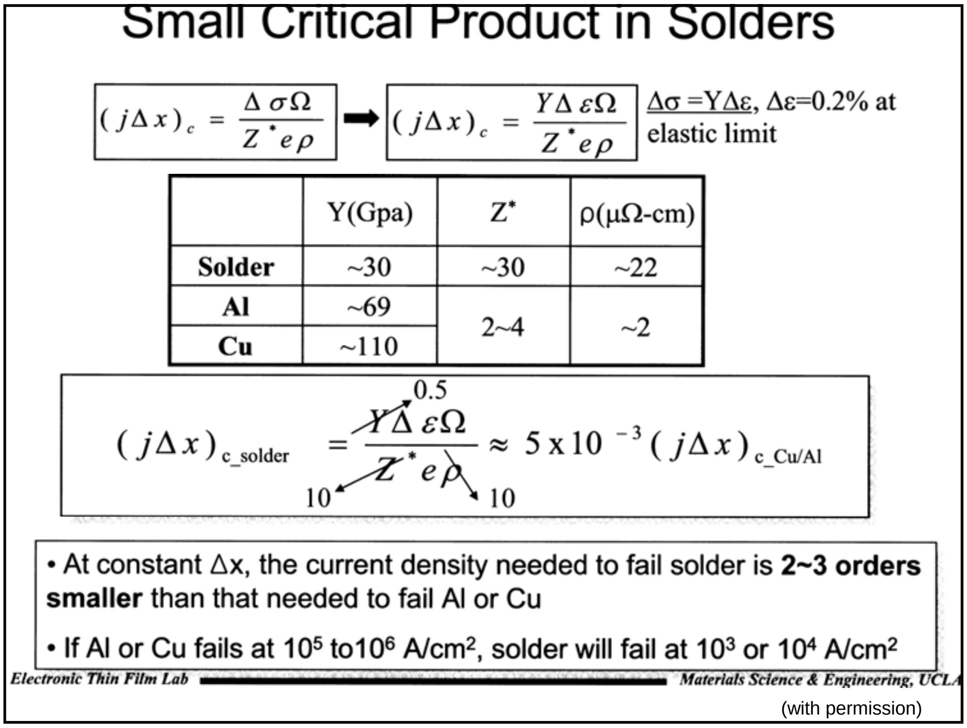


FIG. 6. Schematic diagram of a set of Al strips of different lengths patterned on a base line of TiN. The longer the length, the larger the depletion at the cathode. Below the critical length, there is no electromigration damage as depicted by the last one on the left-hand side.

TABLE I. Melting point and diffusivities of Cu, Al, and eutectic SnPb.

	Melting point (K)	Temperature ratio 373 K/T_m	Diffusivities at 100 °C (cm^2/s)	Diffusivities at 350 °C (cm^2/s)
Cu	1356	0.275	Lattice $D_l=7\times10^{-28}$	$D_l=5\times10^{-17}$
			Grain boundary $D_{gb}=3\times10^{-15}$ Surface $D_s=10^{-12}$	$D_{gb}=1.2\times10^{-9}$ $D_s=10^{-8}$
Al	933	0.4	Lattice $D_l=1.5\times10^{-19}$	$D_l=10^{-11}$
			Grain boundary $D_{gb}=6\times10^{-11}$	$D_{gb}=5\times10^{-7}$
Eutectic SnPb	456	0.82	Lattice $D_l=2\times10^{-9}-2\times10^{-10}$	Molten state $D_l>10^{-5}$



Small Critical Product in Solders

$$\boxed{(j\Delta x)_c = \frac{\Delta\sigma\Omega}{Z^* e\rho}} \Rightarrow \boxed{(j\Delta x)_c = \frac{Y\Delta\varepsilon\Omega}{Z^* e\rho}}$$

$\Delta\sigma = Y\Delta\varepsilon$, $\Delta\varepsilon = 0.2\%$ at elastic limit

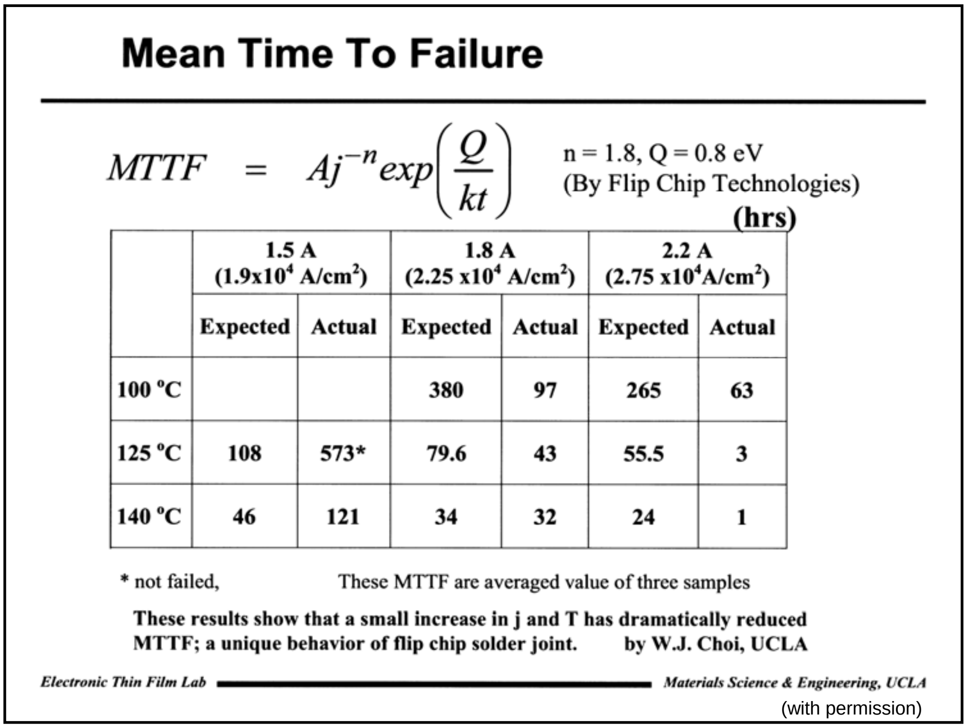
	Y(Gpa)	Z^*	ρ(μΩ-cm)
Solder	~30	~30	~22
Al	~69	2~4	~2
Cu	~110		

$$(j\Delta x)_{c\_solder} = \frac{\overset{0.5}{\cancel{Y}}\Delta\varepsilon\Omega}{\underset{10}{\cancel{Z^*}}\, e\, \underset{10}{\cancel{\rho}}} \approx 5 \times 10^{-3}(j\Delta x)_{c\_Cu/Al}$$

- At constant Δx, the current density needed to fail solder is **2~3 orders smaller** than that needed to fail Al or Cu
- If Al or Cu fails at 10^5 to 10^6 A/cm^2, solder will fail at 10^3 or 10^4 A/cm^2

Electronic Thin Film Lab *Materials Science & Engineering, UCLA*

(with permission)



Mean Time To Failure

$$MTTF = Aj^{-n}exp\left(\frac{Q}{kt}\right)$$

n = 1.8, Q = 0.8 eV
(By Flip Chip Technologies)

(hrs)

	1.5 A (1.9×10^4 A/cm^2)		**1.8 A (2.25×10^4 A/cm^2)**		**2.2 A (2.75×10^4 A/cm^2)**	
	Expected	**Actual**	**Expected**	**Actual**	**Expected**	**Actual**
100 °C			**380**	**97**	**265**	**63**
125 °C	**108**	**573***	**79.6**	**43**	**55.5**	**3**
140 °C	**46**	**121**	**34**	**32**	**24**	**1**

* not failed, These MTTF are averaged value of three samples

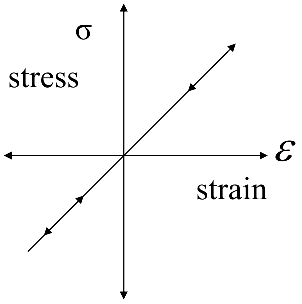
These results show that a small increase in j and T has dramatically reduced MTTF; a unique behavior of flip chip solder joint. by W.J. Choi, UCLA

Electronic Thin Film Lab *Materials Science & Engineering, UCLA*

(with permission)

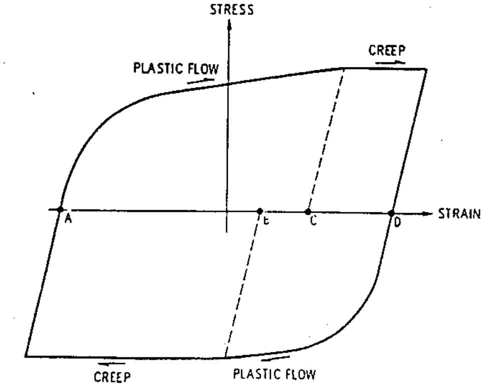
Mechanical and Thermo mechanical Degradation mechanisms

- Mechanical

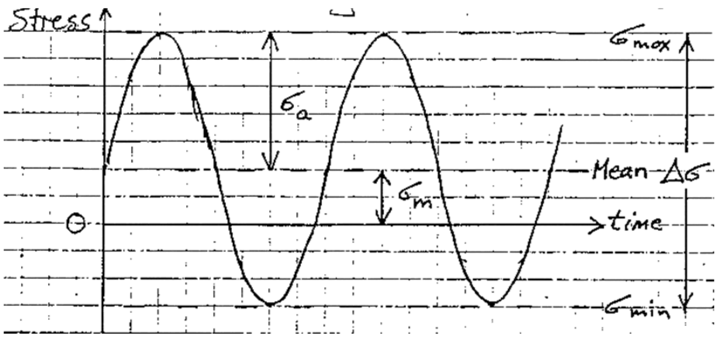


Ideal elastic material

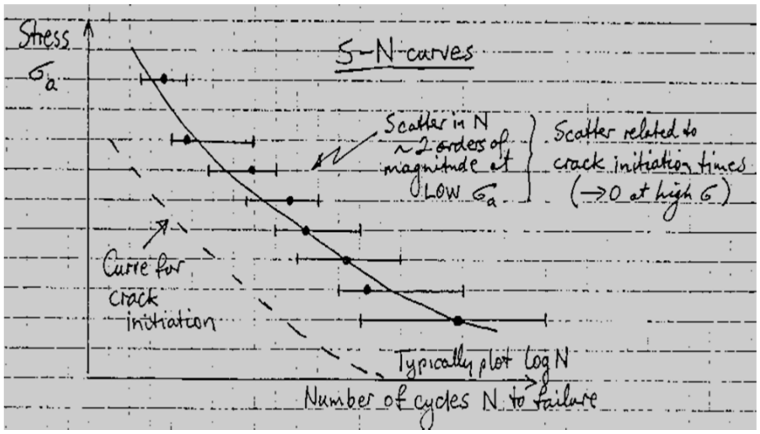
Elastic and plastic deformation



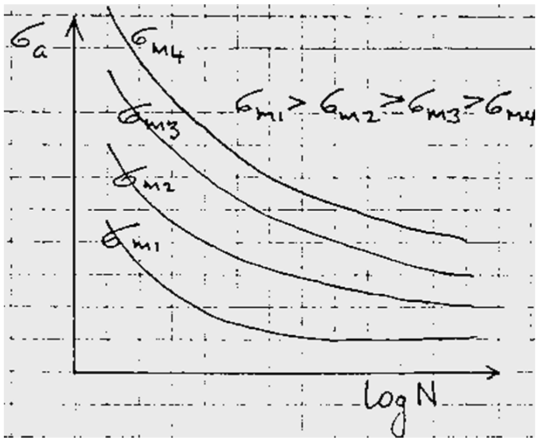
1(a) Mechanical Fatigue Failure

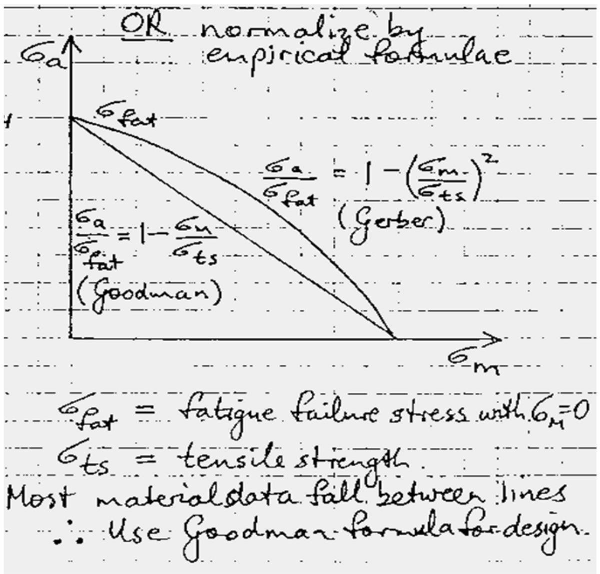


S-N curves



Effect of mean stress σ_m





OR normalize by empirical formulae

$\frac{\sigma_a}{\sigma_{fat}} = 1 - \left(\frac{\sigma_m}{\sigma_{ts}}\right)^2$ (Gerber)

$\frac{\sigma_a}{\sigma_{fat}} = 1 - \frac{\sigma_m}{\sigma_{ts}}$ (Goodman)

σ_{fat} = fatigue failure stress with $\sigma_M = 0$

σ_{ts} = tensile strength

Most material data fall between lines

∴ Use Goodman formula for design.

Coffin-Manson Equation

Elastic

$$\sigma_a = E\frac{\Delta\varepsilon_e}{2} = \sigma_f'(2N_f)^b$$

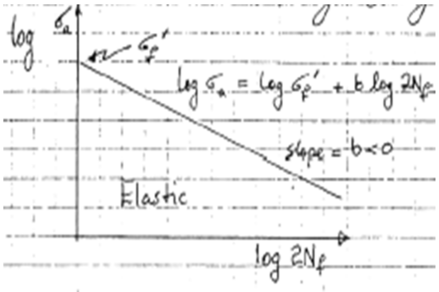
σ_f' = fatigue strength coefficient

= "stress intercept at one load reversal ($2N_f = 1$)"

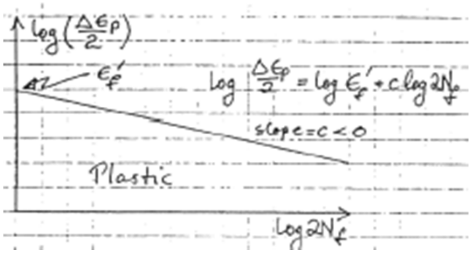
N_f = cycles to fail

$2N_f$ = no. of load reversals to failure

b = failure strength exponent



Elastic



Plastic

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'(2N_f)^c$$

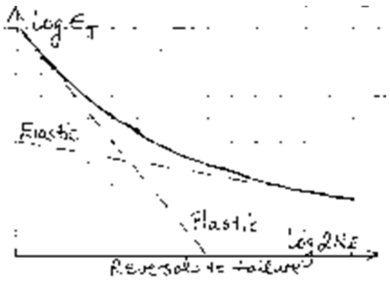
ε_f' = fatigue ductility coefficient

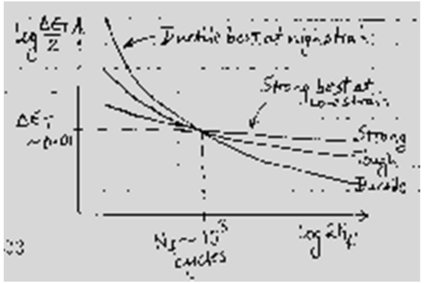
= "strain intercept at one load($2N_f = 1$)"

c = fatigue ductility exponent (.7 < c < -o.5)

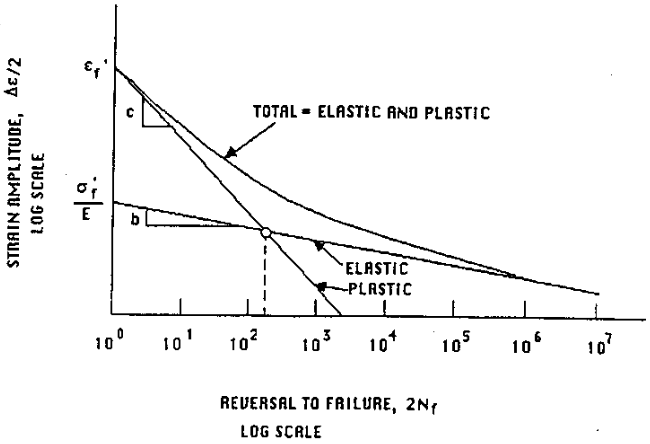
Total strain

$$\frac{\Delta\varepsilon_T}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_\rho}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c$$





Schematic representation of generalized Coffin-Manson relation



Palmer-Miner Cumulative Damage Law

- If number of cycle n_i at stress a_i which would cause failure N_i cycles, etc

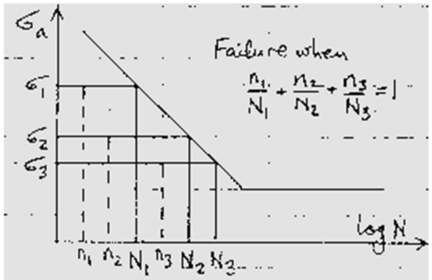
Failure predicted at point where $\sum_{i=1}^{k} \frac{n_i}{N_i} = 1$

$where\ k =$ no. of different stress levels

$\sigma_i =$ i th sterss level

$n_i =$ no. of cycles at σ_i

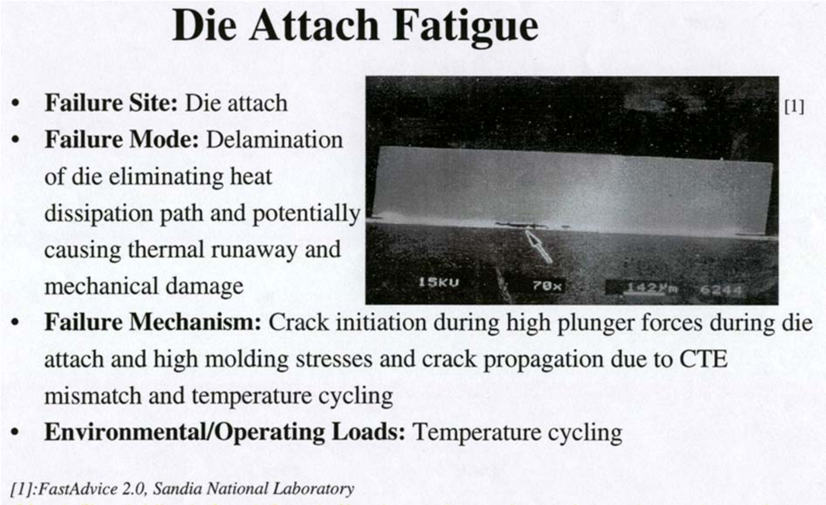
$N_i =$ fatigue life at σ_i



Failure when

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} = 1$$

Fatigue



Die Attach Fatigue

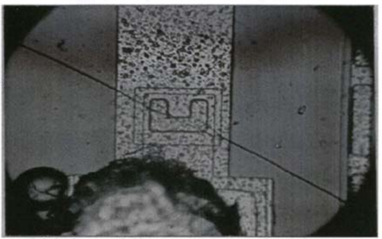
- **Failure Site:** Die attach
- **Failure Mode:** Delamination of die eliminating heat dissipation path and potentially causing thermal runaway and mechanical damage
- **Failure Mechanism:** Crack initiation during high plunger forces during die attach and high molding stresses and crack propagation due to CTE mismatch and temperature cycling
- **Environmental/Operating Loads:** Temperature cycling

[1]

[1]:FastAdvice 2.0, Sandia National Laboratory

Fatigue

Die Fracture and Die Fatigue



- **Failure site:** On chip/die
- **Failure mode:** Open circuit due to fracture
- **Failure mechanism:** Crack initiation during back grinding operation, high plunger forces during die attach and high molding stresses. Crack propagation due to CTE mismatch between the die and the substrate leading to catastrophic failure.
- **Environmental/operating loads:** Temperature, and temperature cycling

[1]:FastAdvice 2.0, Sandia National Laboratory

Fatigue

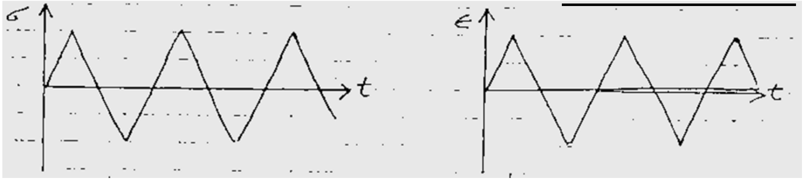
- *There are two ways in which materials can be fatigued:*
    - Mechanical cycle, by applying a sinusoidal stress of constant amplitude.
    - Thermal cycle generates a constant strain

Hence:

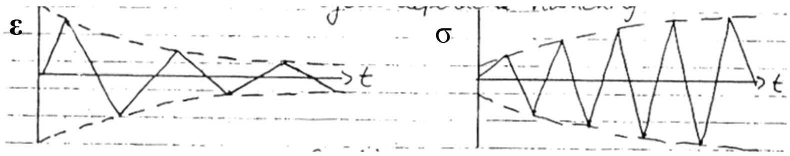
- Stress control for mechanical failure
- Strain control for thermomechanical failure (thermal cycling)

Stress control

Strain control

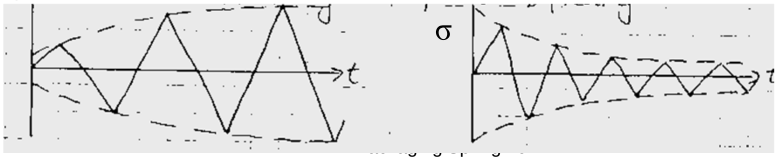


Cyclic dependent hardening



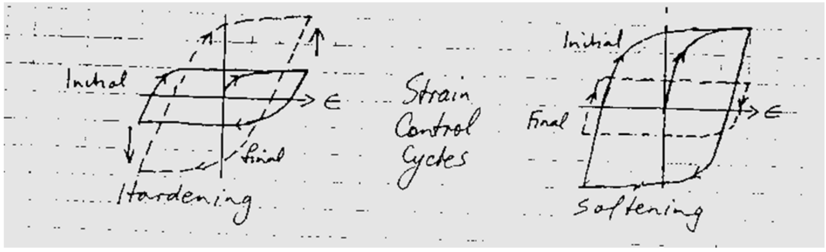
Typical of soft fully annealed metal samples

Cyclic dependent softening



Typical of initially hard cold worked metal samples

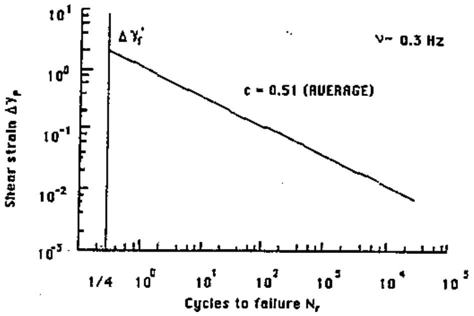
Strain control
Cycles

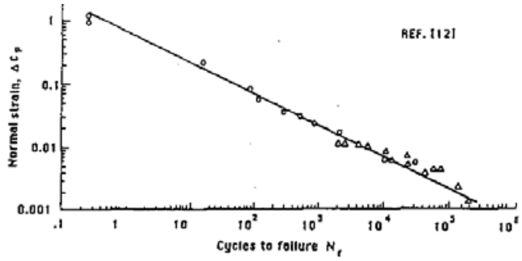


for stable cycles:

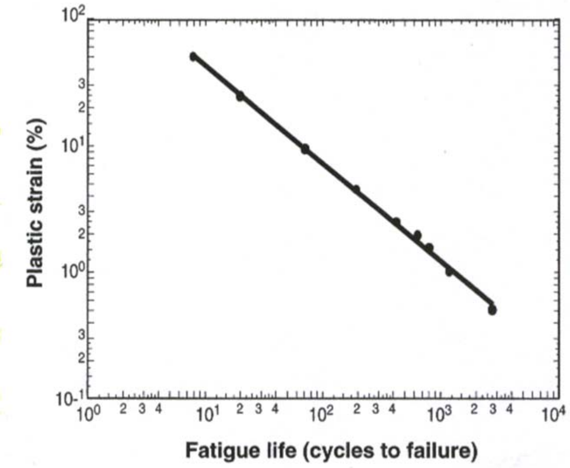
$$\frac{\Delta\varepsilon_T}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_\rho}{2}$$

Plotting the log of the plastic strain amplitude versus the log of the cycles to failure ⟶ a st. line





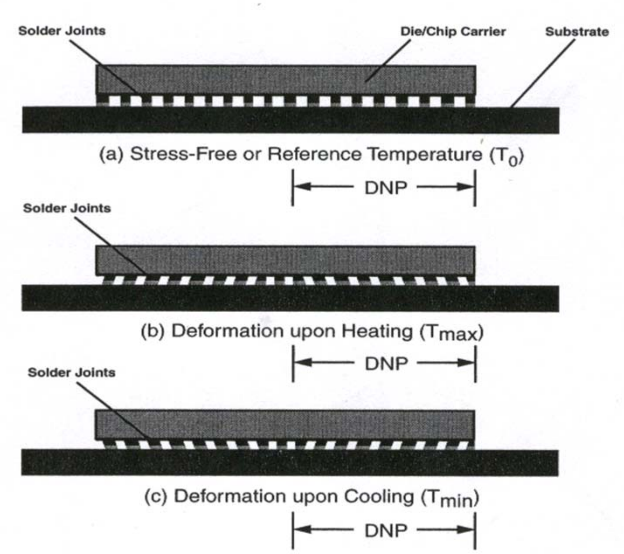
Effect of Plastic strain on fatigue life



Mechanical and Thermomechanical Degradation mechanisms

Thermomechanical

Thermomechanical Deformation in solder joints

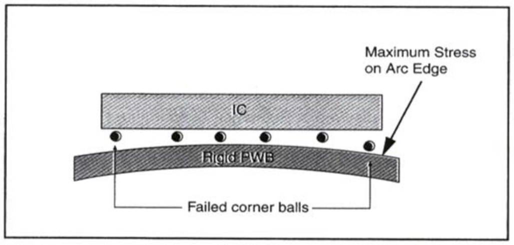


(a) Stress-Free or Reference Temperature (T_0)

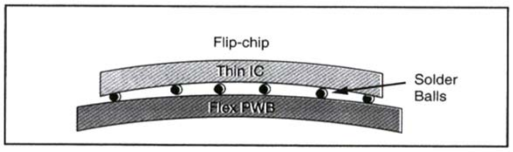
(b) Deformation upon Heating (T_{max})

(c) Deformation upon Cooling (T_{min})

Maximum stress at the edge due to a large DNP (distance from neutral point)

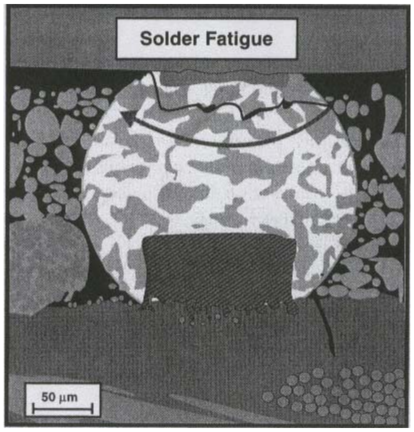


a) Rigid

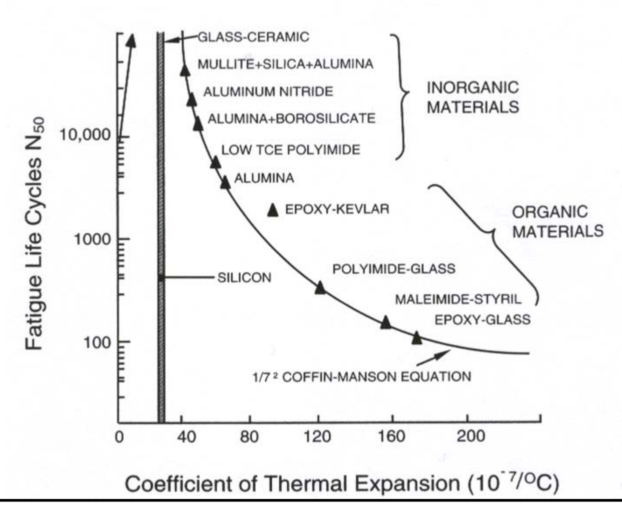


b) Thin or Compliant

Nucleation and propagation of fatigue crack in solder joints



Fatigue life for MCM solder joints on the various substrate materials vs. material's CTE



Plastic Package Failure Mechanisms

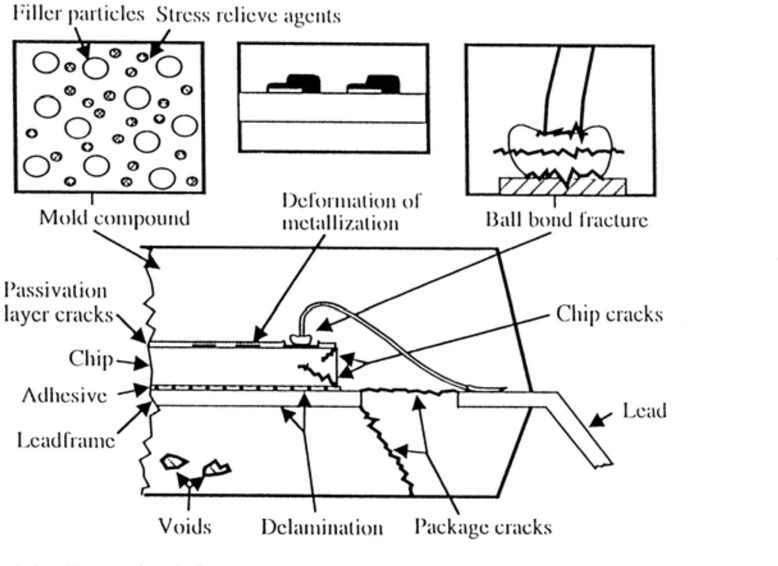
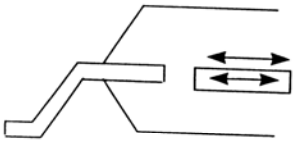
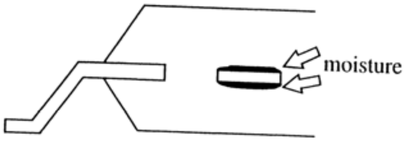


Figure 6.1 *Typical failure mechanisms, sites, and modes in plastic-encapsulated devices*

Thermal & Humidity Modes





1

- thermomechanical stresses due to thermal expansion mismatches

2

- ingress of moisture
- accumulation at interfaces
- rapid localized vaporization of moisture during IR reflow

Popcorn Failure

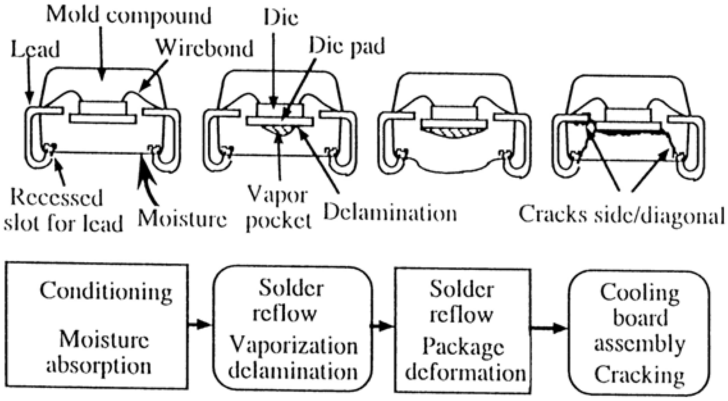


Figure 4.12 *Conditions leading to package popcorning during assembly [Nguyen 1993]*

Popcorn Mechanism

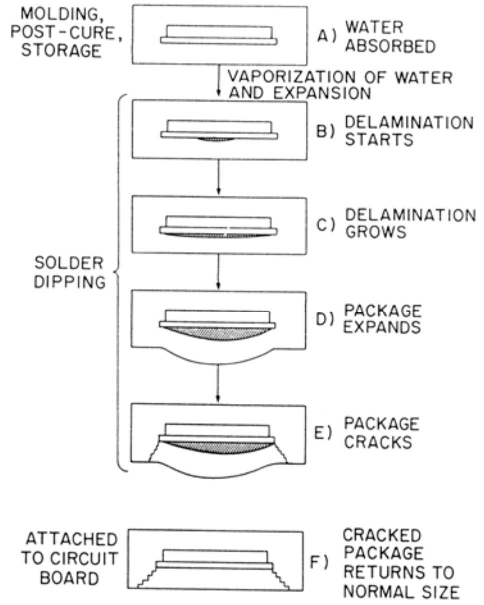
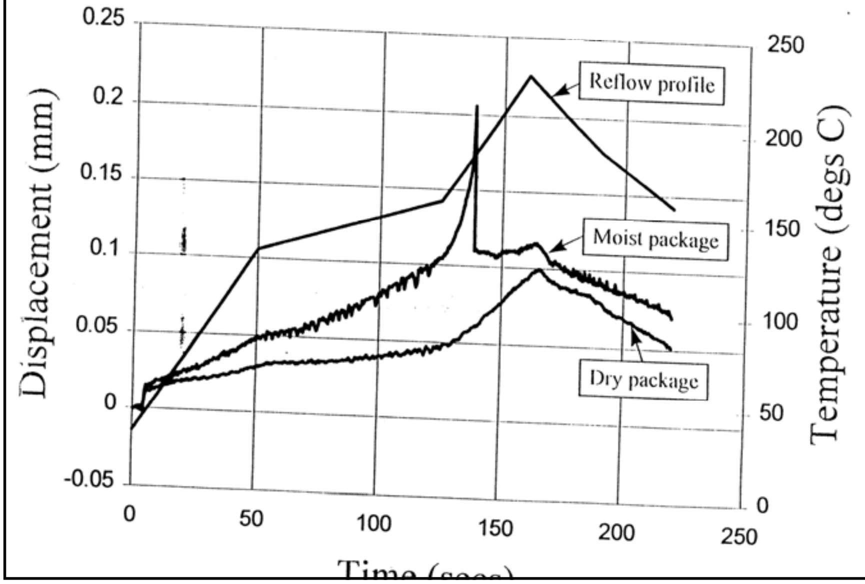
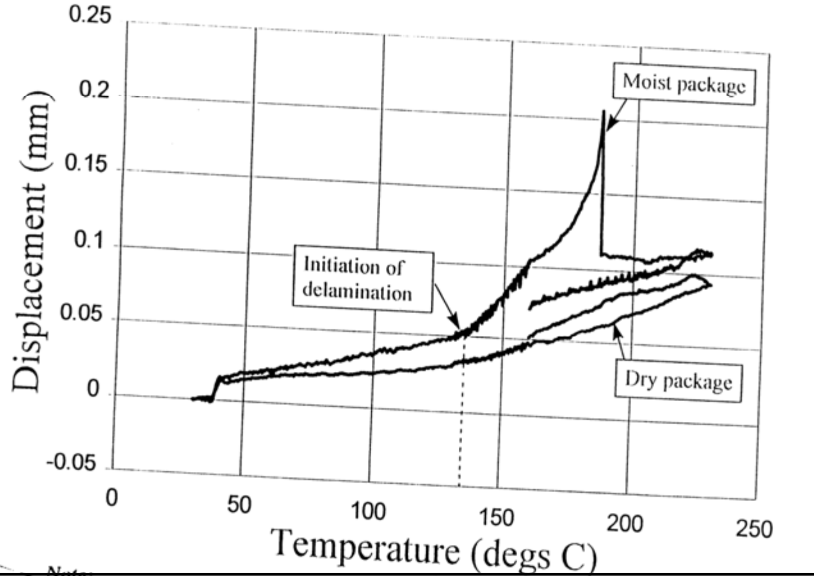


FIGURE 8-8 Mechanism for moisture-induced package cracking on surface mour

Comparision of package deformations for a moisture saturated and dry package plotted vs time

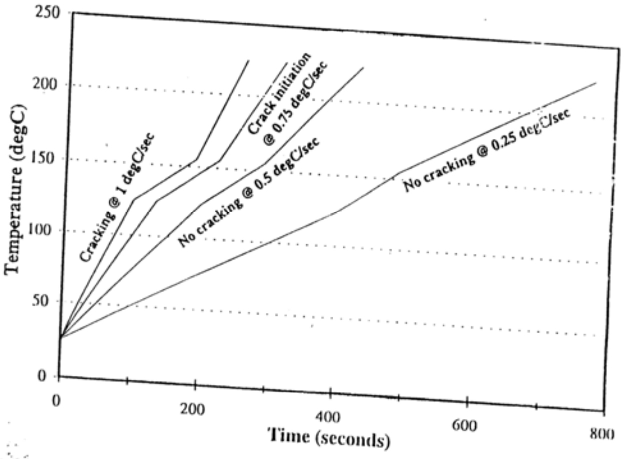


Comparision of package deformations for a moisture saturated and dry package plotted vs temperature



Optimum reflow temperature ramp rates

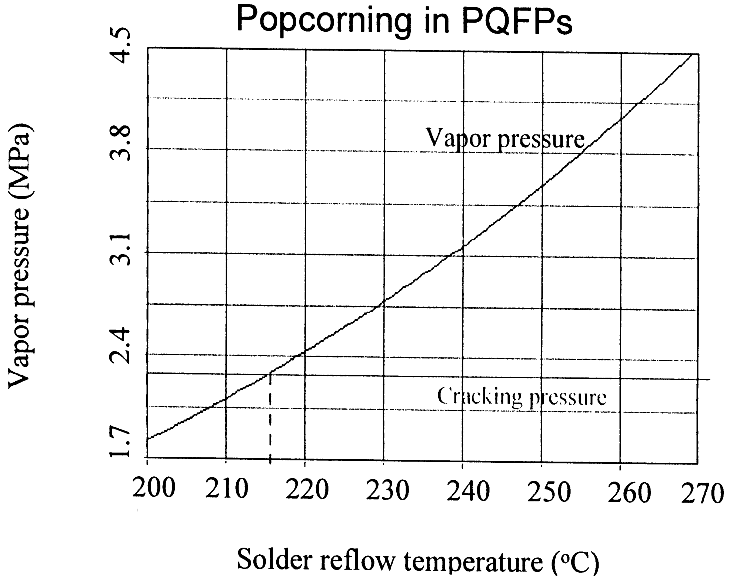
Here, a ramp rate between 0.50 and 0.75°C/sec was found to be optimum for devices preconditioned at Level-1.



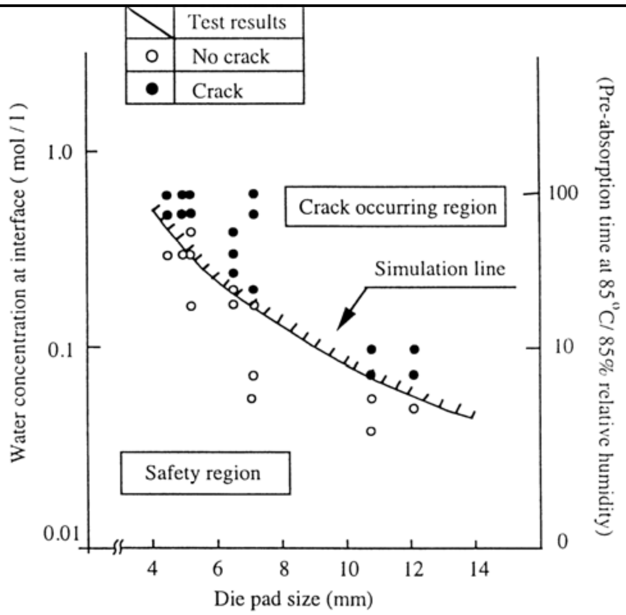
CALCE Electronic Packaging Research Center

University of Maryland

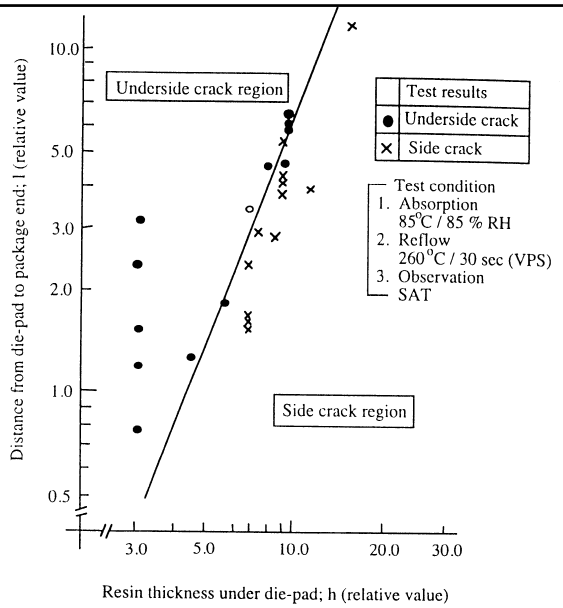
Popcorning in PQFPs



- ***Provide manufacturing process guidelines***



ure **4.14** *Correlation of 260 °C dip soldering induced plastic quad flatpa cking with varying die-pad sizes [Matsushita Electric Industri rporation 1993]*



gure 4.15 *Correlation of 260 °C dip soldering-induced small-outline J ckage cracking with the distance from die-paddle edge to package an ckness of encapsulant under the die paddle for underside cracks or side c*

Packing Materials

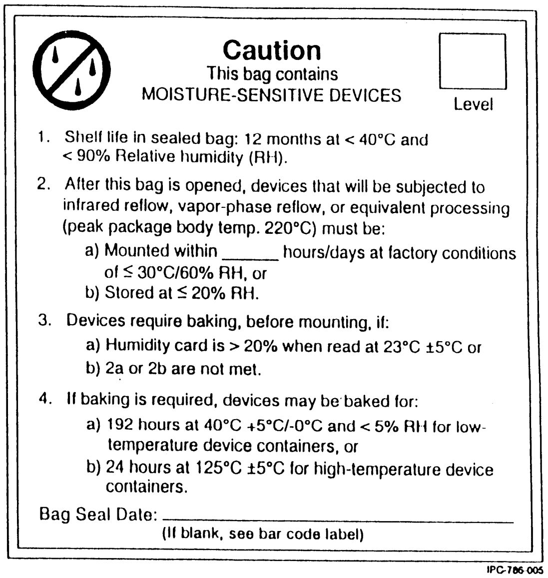
Caution label

Affixed to the outside surface of the moisture barrier bag.

The label provides:

- Factory seal date
- Shelf life in bag
- Shelf life out of bag (classification level)
- Baking instructions

Dry Packing



Caution
This bag contains
MOISTURE-SENSITIVE DEVICES

☐ Level

1. Shelf life in sealed bag: 12 months at < 40°C and < 90% Relative humidity (RH).
2. After this bag is opened, devices that will be subjected to infrared reflow, vapor-phase reflow, or equivalent processing (peak package body temp. 220°C) must be:
   a) Mounted within ______ hours/days at factory conditions of ≤ 30°C/60% RH, or
   b) Stored at ≤ 20% RH.
3. Devices require baking, before mounting, if:
   a) Humidity card is > 20% when read at 23°C ±5°C or
   b) 2a or 2b are not met.
4. If baking is required, devices may be baked for:
   a) 192 hours at 40°C +5°C/-0°C and < 5% RH for low-temperature device containers, or
   b) 24 hours at 125°C ±5°C for high-temperature device containers.

Bag Seal Date: ______________________
(If blank, see bar code label)

IPC-786-005