Package Reliability
TKK 2009 Lecture 3 Parts A & B1

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Package Reliability

- A. Reliability Theory
  - Reliability (bathtub curve), PDF, cumulative failure function
  - Hazard rate, mean time to failure
  - Exponential distribution
  - Weibull distribution
  - System reliability
  - Accelerated testing
  - Plotting failure distributions
- B. Package Failure Mechanisms

Potential consequences of poor reliability

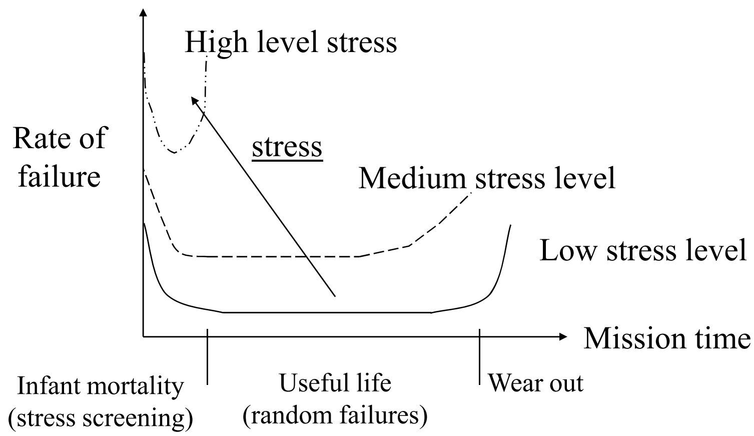
Customer	Supplier/Vendor
Loss of Product	Warranty claims
Loss of product capability	Production downtime
Production downtime	Test and repair cost
Spare parts and maintenance	Diminished confidence and image
Loss opportunities	Loss of future business

Reliability & Failure

- *Reliability*: The reliability of a product is the probability that the product will perform satisfactorily for a given time at a desired confidence level under specified operating and environmental conditions.
- *Failure* is defined as the loss of the ability of the product to perform a required operation in a specific environment.
- *Three types of failure* according to when a failure occurred during a product's operating life:
    - **Infant mortality**
    - **"Useful" life**
    - **Wear-out failure**

The Bathtub Curve

- If a plot of the rate failure of a product versus its operating life is constructed from data taken a large sample of identical products placed in operation at t=0



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Reliability Theory

- Sample size = n_o
- Number failed at time t = $n_f(t)$
- Number still operating satisfactorily = $n_s(t)$

$$n_f(t) + n_s(t) = n_o$$

- Reliability = $R(t)$ and "Unreliability" = $Q(t)$
- Probability device "ok"

$$R(t) = n_s(t)/n_o = 1 - n_f(t)/n_o = 1 - Q(t)$$

$$Q(t) = n_f(t)/n_o = 1 - n_s(t)/n_o = 1 - R(t)$$

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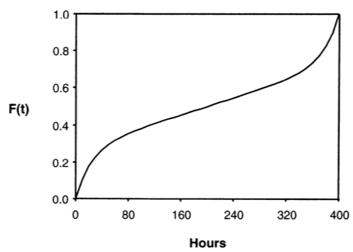
Failure Probability Density Function (PDF)

- Failure probability function $f(t)$

$$f(t) = (1/n_o)\frac{d}{dt}n_f(t) = \frac{dQ(t)}{dt} = -\frac{dR(t)}{dt}$$

- Cumulative failure function $\therefore Q(t) = \int_0^t f(\tau)d\tau = \frac{n_f(t)}{n_o} = F(t)$
- Similarly $R(t) = \frac{n_s(t)}{n_0} = \int_t^{\infty} f(\tau)d\tau$ and $\int_0^{\infty} f(\tau)d\tau = 1$

FIGURE 22.3 A Typical cumulative failure function, F(t).



F(t) here corresponds to the three regions of the bathtub curve

Hazard Rate ("force of mortality")

- The Hazard Rate is defined as the number of failures per unit time per number of operational parts left.

$$\lambda(t) = \frac{1}{n_s(t)}\frac{dn_f(t)}{dt} = \frac{1}{R(t)}\frac{dQ(t)}{dt} = \frac{-1}{R(t)}\frac{d[R(t)]}{dt} = \frac{f(t)}{R(t)}$$

Note $\lambda(t) = [dn_f(t)/dt]/n_s \approx f(t) = [dn_f(t)/dt]/n_0$ if $n_s \approx n_0$
i.e. if few failures yet

- Cumulative Hazard Rate: $H(t) = \int_0^t \lambda(t) = -\ln R(t)$
since R(0)=1
- Mean Time to Failure (MTTF):

$$MTTF = \int_0^{\infty} t.f(t)dt \Rightarrow \int_0^{\infty} R(t)dt$$ if $R(t) \to 0$ for $t \ll \infty$.

Reliability relationships, for $n_f(t)$ failed and $n_s(t)$ surviving at time t of an initial sample of n_0.

Function	Definition	General	2-parameter Weibull (γ=0)	Exponential (η=1, β=1)	Rayleigh (β=2, k=2/η²)
Probability density function f(t)	$\frac{1}{n_0}\frac{dn_f(t)}{dt}$	$\frac{dQ(t)}{dt} = -\frac{dR(t)}{dt}$	$\frac{\beta}{\eta}\left[\frac{t}{\eta}\right]^{\beta-1} exp - \left[\frac{t}{\eta}\right]^{\beta}$	$\lambda_0 . exp(-\lambda_0 t)$	$kt.exp\text{-}\frac{1}{2}kt^2$
Survivor function (reliability) R(t)	$\frac{n_s(t)}{n_0}$	$\int_t^{\infty} f(\tau)d\tau$	$exp - \left[\frac{t}{\eta}\right]^{\beta}$	$e^{-\lambda_0 t}$	$exp\text{-}\frac{1}{2}kt^2$
Cumulative failure function (unreliability) Q(t)=1-R(t)=F(t)	$\frac{n_f(t)}{n_0}$	$\int_0^{t} f(\tau)d\tau$	$1\text{-}exp - \left[\frac{t-\gamma}{\eta}\right]^{\beta}$	$1\text{-} e^{-\lambda_0 t}$	$1\text{-} exp\text{-}\frac{1}{2}kt^2$
Hazard rate λ(t)	$\frac{1}{n_s(t)}\frac{dn_f(t)}{dt}$	$\frac{-1}{R(t)}\frac{dR(t)}{dt} = \frac{f(t)}{R(t)}$	$\frac{\beta}{\eta}\left[\frac{t}{\eta}\right]^{\beta-1}$	λ_0	kt
Cumulative hazard rate H(t)	$\int_0^{t} \lambda(\tau)d\tau$	$-\ln R(t)$	$\left[\frac{t}{\eta}\right]^{\beta}$	$\lambda_0 t$	kt^2
Mean time to failure MTTF	$\int_0^{\infty} t.f(t)dt$	$\int_0^{\infty} R(t)dt,$		$1/\lambda_0$	

Example: Exponential Distribution

- Most commonly used with wide application in electronic systems. It is a single parameter distribution.

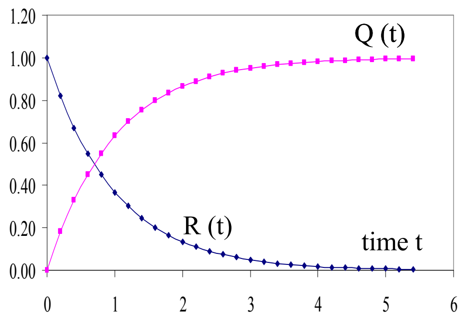
$$f(t) = \lambda_o \exp^{(-\lambda_o t)} . u(t)$$

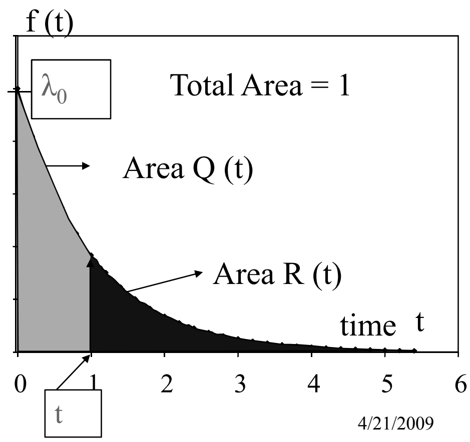
- where $u(t)$ is the Heavyside step function and λ_o is called the chance hazard rate.

- $R(t) = \int_t^{\infty} f(\tau)d\tau = \int_t^{\infty} \lambda_o \exp(-\lambda_o \tau).d\tau = -\exp(-\lambda_0 \tau)]_t^{\infty} = \exp - (\lambda_0 t)$

- $Q(t) = 1 - R(t)$ and $\int_0^{\infty} f(\tau)d\tau = 1$

Exponential Distribution





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Hazard Rate ("force of mortality")

$$\lambda(t) = \frac{1}{n_s(t)} \frac{dn_f(t)}{dt} \xrightarrow{(\div n_0)}$$

$$\Rightarrow \frac{1}{R(t)} \frac{dQ(t)}{dt} = -\frac{dR(t)}{dt} \Big/ R(t) \quad \Rightarrow -\frac{\left(-\lambda_0 \exp^{-\lambda_0 t}\right)}{\exp^{-\lambda_0 t}} = \lambda_0$$

for exponential (Failure frequency at time t)

Mean Time to Failure MTTF

$$MTTF = \int_0^\infty t.f(t)dt \quad \Rightarrow \int_0^\infty R(t)dt$$

$$= \frac{1}{\lambda_0} \exp\left(\frac{-\lambda_0}{t}\right)\Big]_0^\infty = \frac{1}{\lambda_0}$$

for exponential distribution

i.e. interpret Reliability $R(t) = \exp\left(\frac{-t}{MTTF}\right)$

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Weibull Distribution

$f_w(t)$ is Weibull probability distribution function, where

$$f_w(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \exp-\left(\frac{t-\gamma}{\eta}\right)^{\beta} \longrightarrow \text{"3-parameter distribution"}$$

$$R(t) = \exp^{-\frac{(t-\gamma)^{\beta}}{\eta}}$$

$\gamma = 0 \longrightarrow$ "2-parameter Weibull"

$\beta = 1, \gamma = 0, \eta = \lambda_o^{-1} \longrightarrow$ exponential

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Weibull Distribution

- β > 0 is "shape factor"
  - 0< β< 1 early failure
  - β =1 constant rate
  - β >1 wear out
- η>0 is "scale factor"
- γ is location parameter
  - γ < 0 pre-existing failure (storage, transport)
  - γ = 0 failure begins t = 0
  - γ > 0 failure free period t = 0

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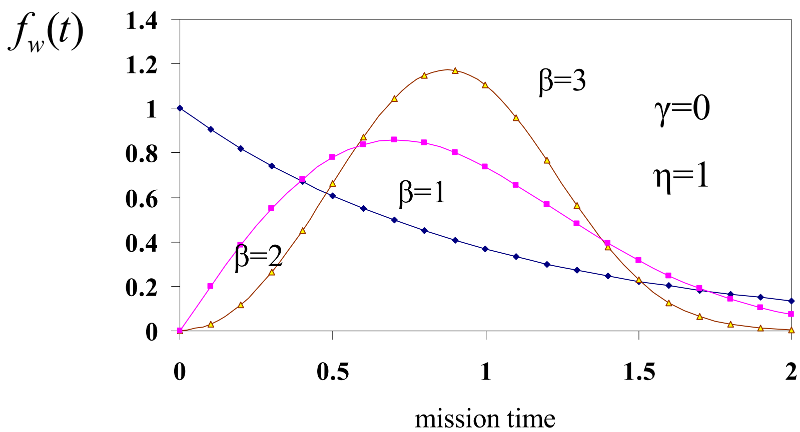
Weibull Distribution



Effect of shape parameter

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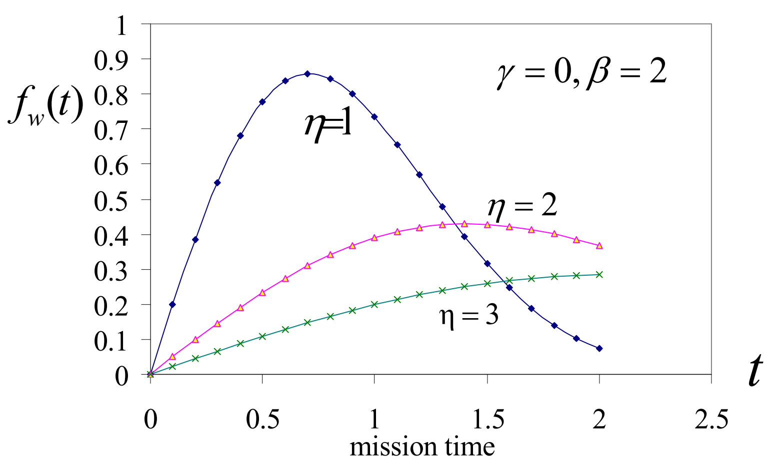
Weibull Distribution



Effect of scale parameter

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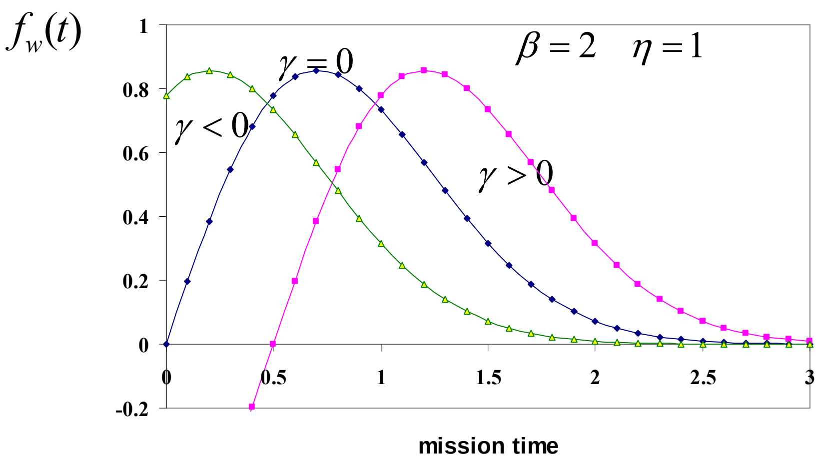
Weibull Distribution



Effect of location parameter

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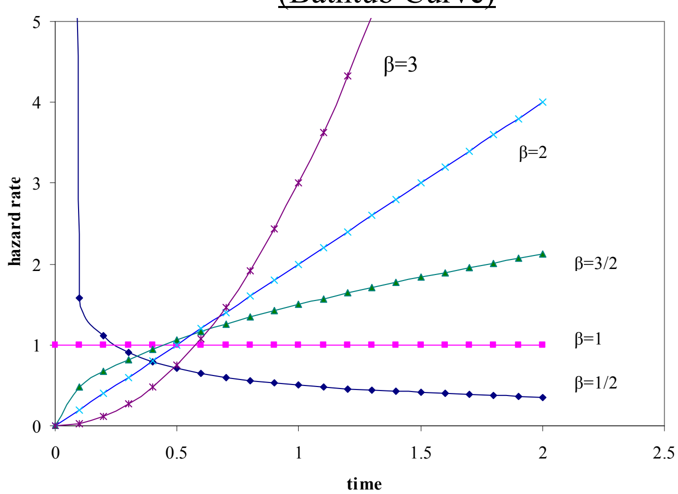
Weibull Distribution: Hazard Rate

(Bathtub Curve)



Effects of shape parameter β

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Series Reliability

- Failure of a system if any components fails. It is function of the weakest link in the system.

$$R_{ss} = \prod_{i=1}^{n} R_i = R_1.R_2.R_3...R_n,$$

$$\lambda_{ss} = \sum_{1}^{n} \lambda_i$$

$$MTTF_{ss} = \frac{1}{\lambda_{ss}}$$

Parallel Reliability

- If there are n redundant components $R_{ps} = 1 - Q_{ps} = 1 - \prod_{i=1}^{n}(1 - R_i)$

note: for n=2

$$\lambda_{ps} = \frac{\lambda_1 e^{-\lambda_1 t} + \lambda_2 e^{-\lambda_2 t} - (\lambda_1 + \lambda_2) e^{-(\lambda_1 + \lambda_2)t}}{e^{-\lambda_1 t} + e^{-\lambda_2 t} - e^{-(\lambda_1 + \lambda_2)t}}$$

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Effect of series complexity on system reliability

No. of Components in series	System reliability for individual component reliability of			
	99.999%	99.99%	99.90%	99.00%
10	99.99%	99.90%	99.004%	90.44%
100	99.90%	99.01%	90.48%	36.60%
250	99.50%	99531%	77.87%	8.1%
500	99.50%	99.12%	60.64%	0.66%
1000	99.01%	99.48%	36.77%	0.004%

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Accelerated Testing

- Failure Mechanism (diffusion, corrosion, etc)

$$r = r_0 \exp^{-E_0/kT}$$

So, accelerated at higher temperature

$$\text{time to failure } \alpha \ 1/r$$

So, Times to failure t_1 at T_1, t_2 at T_2

$$\frac{t_1}{t_2} = \exp \frac{E_0}{k} \left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

Acceleration factor

$t_1 / t_2 > 1 \quad T_1 < T_2$

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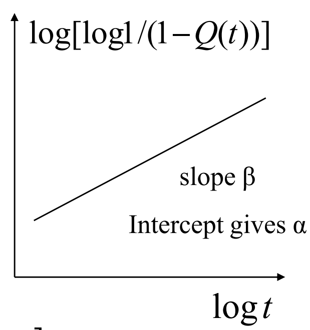
Plotting :Weibull Distribution

$$Q(t) = 1 - \exp^{-(t/\alpha)^{\beta}}$$

$$\ln\{1 - Q(t)\} = -(t/\alpha)^{\beta}$$

$$\ln\{-\ln[1 - Q(t)] = \beta \ln t - \beta \ln \alpha$$



or use Cumulative Hazard rate

$$H(t) = \int_0^t \lambda(t)dt = -\ln[R(t)] = -\ln[1 - Q(t)]$$

$$\therefore \text{ plot } \log H(t) \text{ vs } \log t$$

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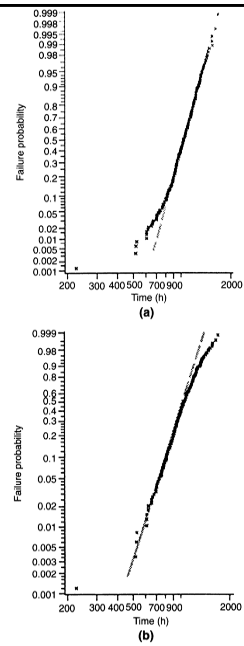
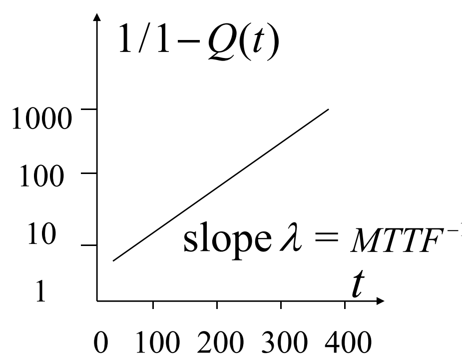


Figs. 4-12 Light-bulb failure times plotted in terms of lognormal (a) and Weibull (b) distribution functions. From F. R. Nash, *Estimating Device Reliability: Assessment of Credibility,* Kluwer Academic, Boston (1993)

Plotting: Exponential Distribution

$$Q(t) = 1 - \exp^{-\lambda t}$$

$$\therefore H(t) = \ln \frac{1}{1 - Q(t)} = \lambda t$$



B. Failure Mechanisms and Modeling

1. Mechanical and Thermomechanical Degradation mechanisms
   - a. Fatigue (Fracture Mechanics)
   - b. Creep
   - c. Stress corrosion cracking
2. Thermo- and Electrotransport Fail Mechanisms
   - a. Electromigration
   - b. Thermomigration
3. Electrical and Thermal Degradation Mechanisms
   - a. Dielectric degradation & breakdown
   - b. Contact resistance degradation due to oxidation
4. MIL-HDBK-217 and Physics of Failure
5. Chemical and electrochemical failure mechanisms
   - a. Corrosion
   - b. Wet and Dry Migration
6. Plastic Package Failures
   - a. Popcorning
   - b. Dry Packing
7. Distributions of Failures

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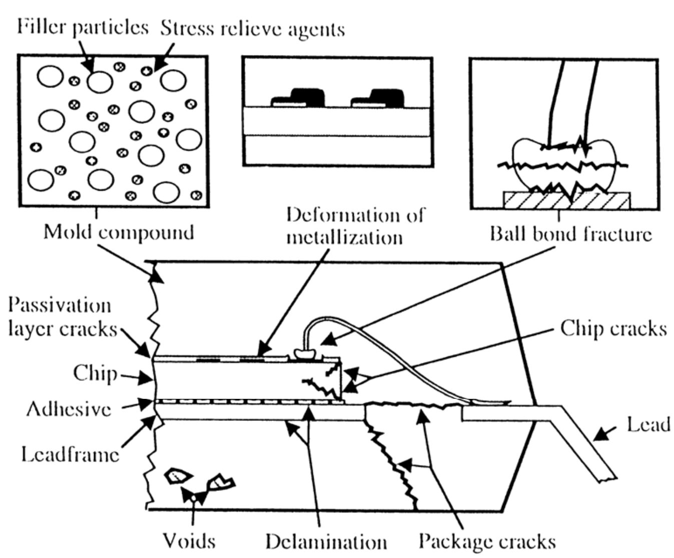
Plastic Package Failure Mechanisms



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

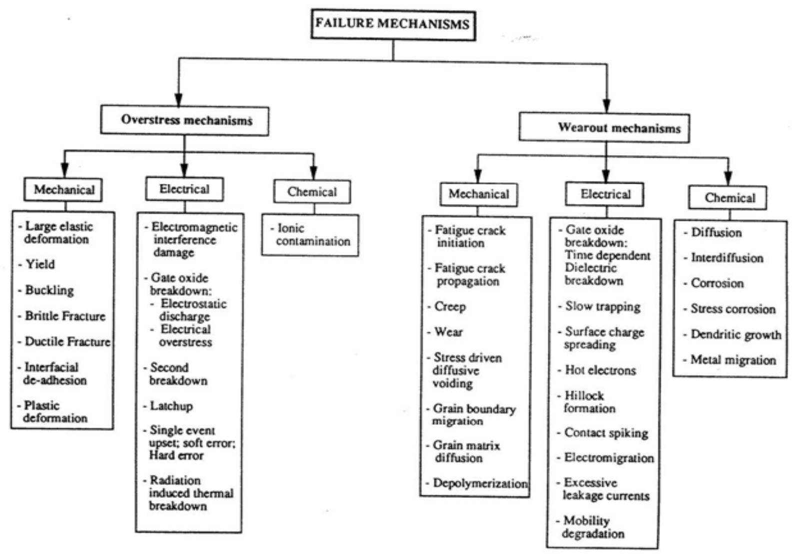


Figure 2.1 *Classification of failure mechanisms*

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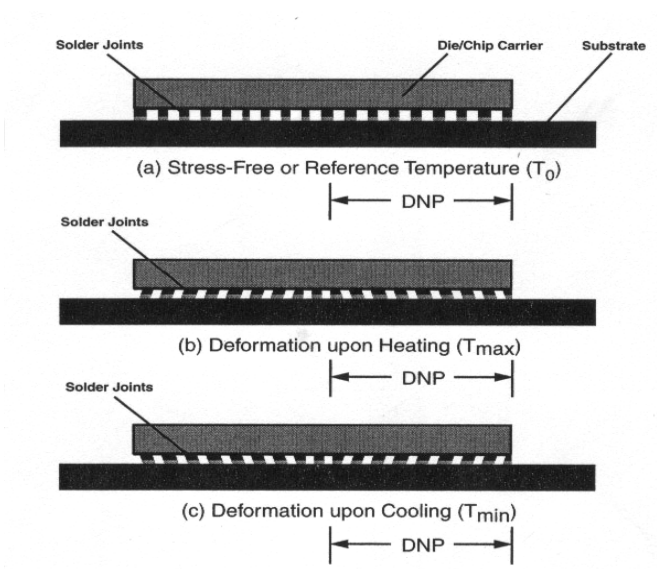
1. Thermomechanical Deformation in solder joints



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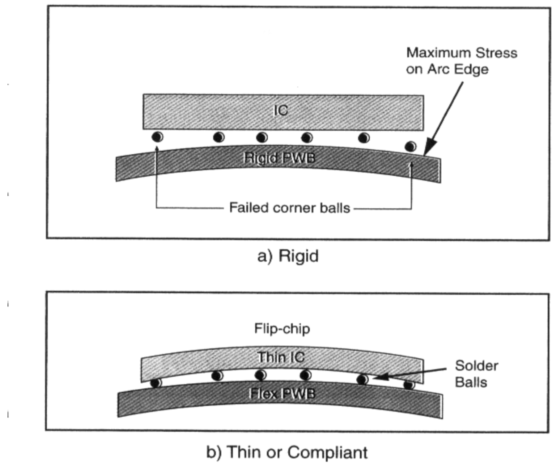
Maximum stress at the edge due to a large DNP (distance from neutral point)



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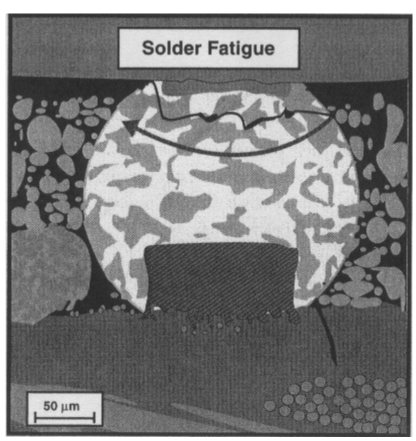
Nucleation and propagation of fatigue crack in solder joints



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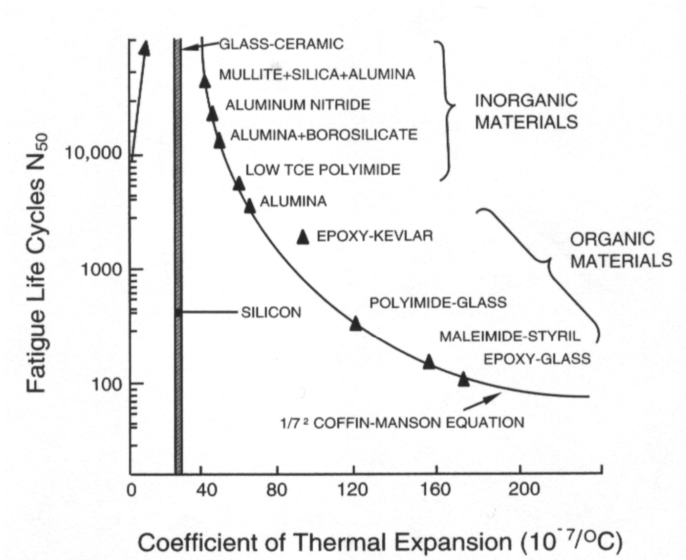
Fatigue life for MCM solder joints on the various substrate materials vs. material's CTE



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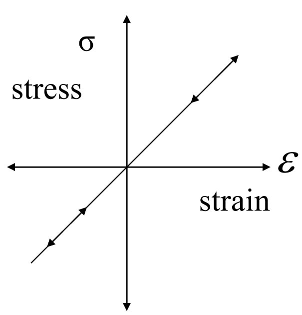
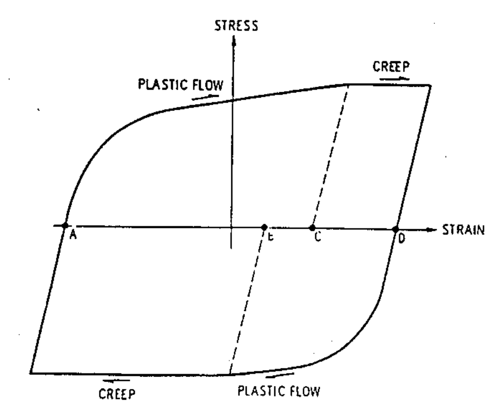
Mechanical and Thermo-mechanical Degradation Mechanisms

- Mechanical

Elastic and plastic deformation



Ideal elastic material



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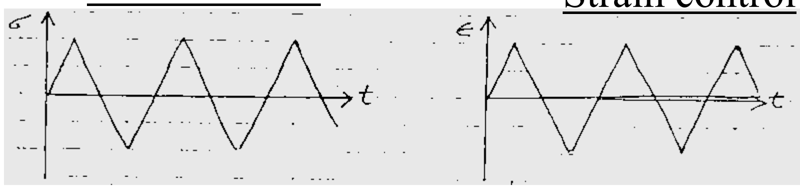
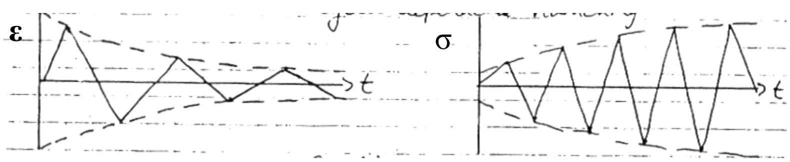
Stress control / Strain control

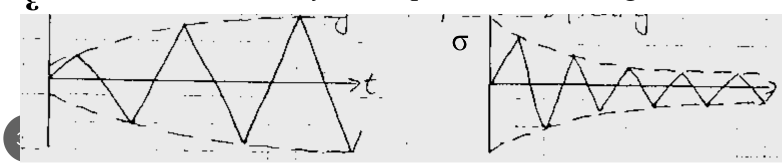


Cyclic dependent hardening



Typical of soft fully annealed metal samples

Cyclic dependent softening



Typical of initially hard cold worked metal samples

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Cyclic Mechanical Testing: Coffin-Manson Equation

Elastic

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

σ_f' = fatigue strength coefficient

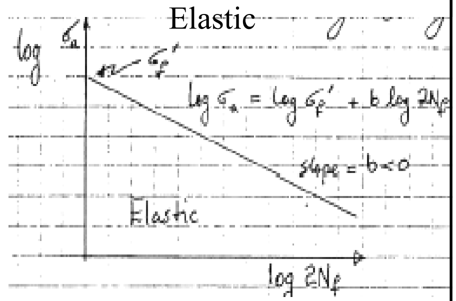
= "stress intercept at one load reversal ($2N_f = 1$)"

N_f = cycles to fail

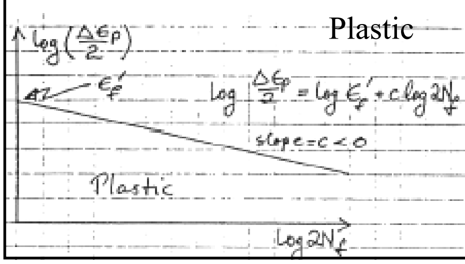
$2N_f$ = no. of load reversals to failure

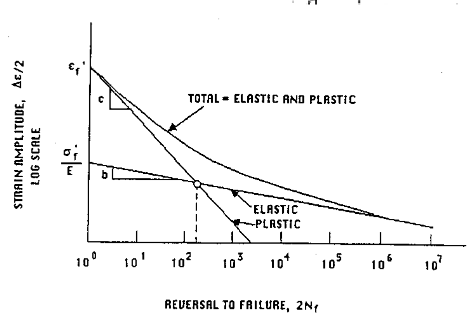
b = failure strength exponent

Elastic



Plastic





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

σ_i = i th sterss level

n_i = no. of cycles at σ_i

N_i = fatigue life at σ_i

Failure when

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