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Lifetime Model for Solder Layers

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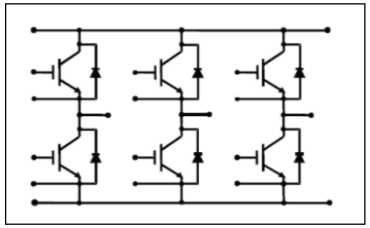
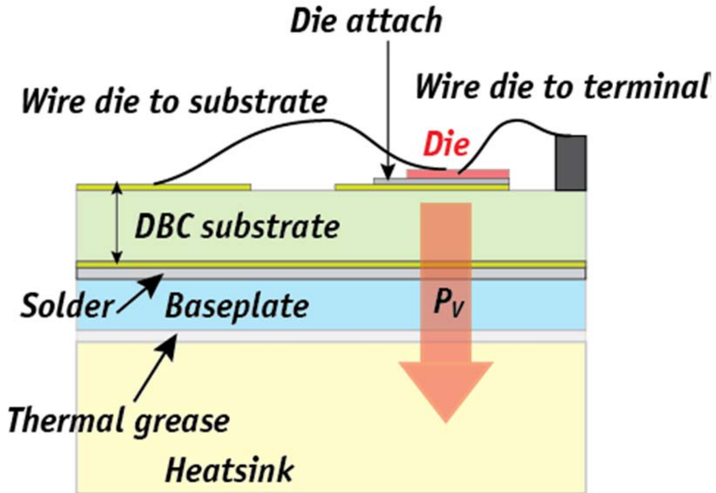
Overview

- Reliability of Power Modules
- Failure Mechanism of Power Modules
  - *Power Cycling (PC) tests, Temperature Cycling (TC) tests*
- Analytical vs. Physical Lifetime Modeling
- Physical lifetime model based on Clech's algorithm for Solder Interconnections
- Solder Interconnection Failure
  - *Solder equations (elastic, plastic and creep deformation)*
  - *Energy-based modeling*
- Lifetime Estimation based on PC tests

Reliability of Power Modules

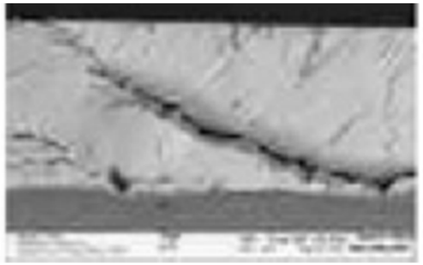
- Power Module: layers with typically different thermal constants have great influence on heating and cooling rate of module
- Thermo-mechanical Stress: temperature gradients and *CTE* (Coefficient of Thermal Expansion) difference between layers
- Mission Profile
- Lifetime Modeling



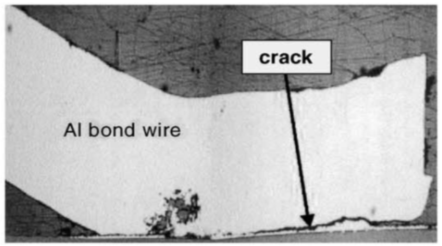


Failure of Power Modules

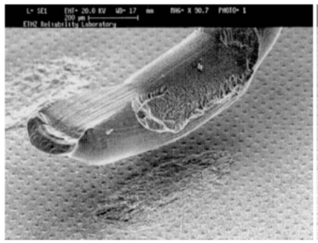
- Bond wire fatigue (lift off, heel cracking)
- Aluminium reconstruction
- Brittle cracking, fatigue crack propagation
- Corrosion of interconnections
- Solder fatigue
- Burnout failures



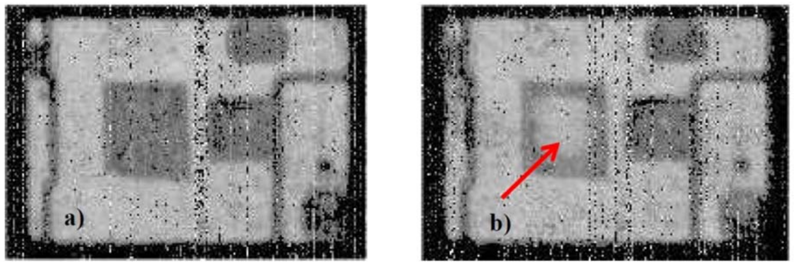
Ref [D. C. Katsis,"Thermal Characterization of Die-Attach Degradation in the Power MOSFET"]



Ref [Lefranc, G., et al. (2003) "Aluminium bond-wire properties after 1 billion cycles"]



Ref [Lefranc, G., eta al. (2003) "Aluminium bond-wire properties after 1 billion cycles"]



Ref [U. Scheuermann, R. Schmidt (EPE 2011), "Impact of Solder Fatigue on Module Lifetime in Power Cycling Tests"]

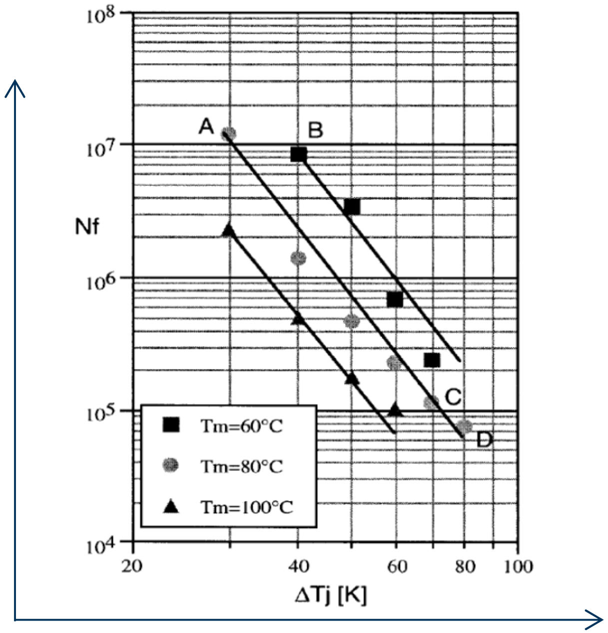
Lifetime Modeling – Analytical Models

- **Basic N_f Model: Coffin-Manson**

$$N_{\mathrm{f}} = a \cdot (\Delta T_{\mathrm{cyc}})^{-n}$$

$$N_{\mathrm{f}} = a \cdot (\Delta T_{\mathrm{cyc}})^{-n} \exp\left(\frac{E_{\mathrm{A}}}{k_{\mathrm{B}} T_{\mathrm{jm}}}\right)$$

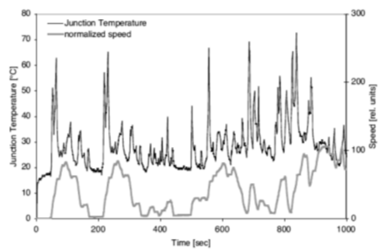
N_f – Number of Cycles to Failure



ΔT_j - Junction Temperature Swing

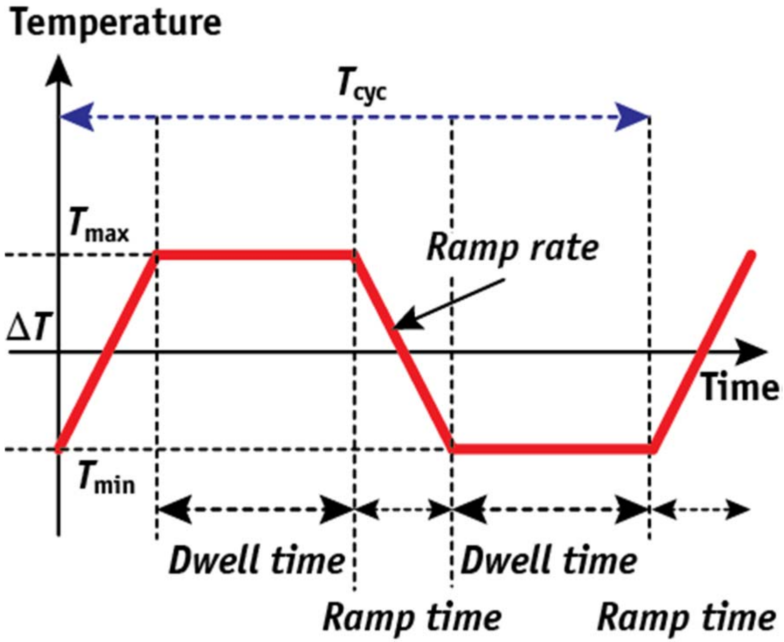
Rain Flow Algorithm
(counting ΔT_{cyc} in mission profile)
+ Miner's rule

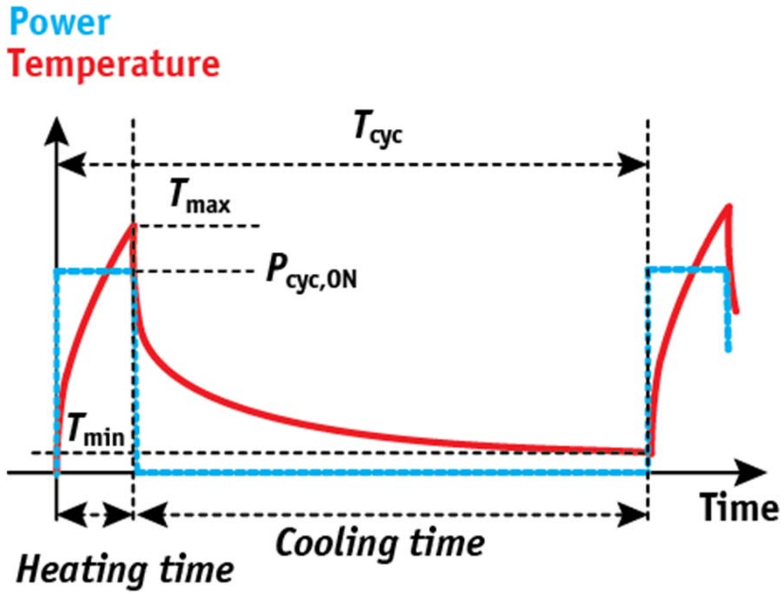
$$\frac{1}{MTTF} = \sum \frac{n_i}{N_{fi}}$$



Accelerated Power Cycling Tests

■ Accelerated Power Cycling Tests





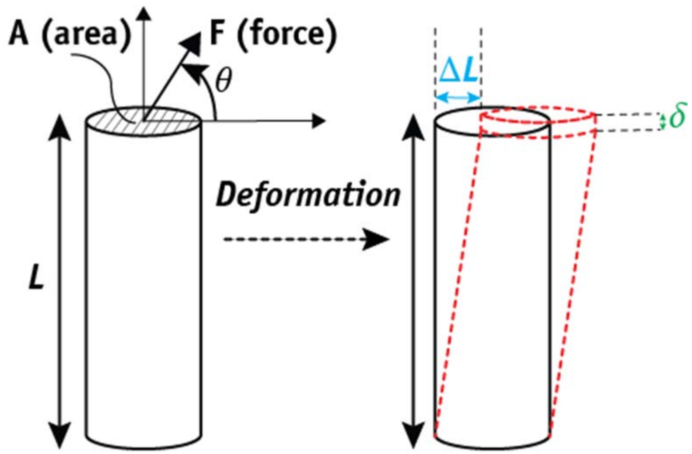
Lifetime Modeling – Physical Models

- Failure and deformation mechanism have to be known in advance

  * Bond Wire Lift-off : Crack Propagation

  * Solder Failure: Stress-/Strain-/Damage /Energy-based model

- Thermo-mechanical behaviour: stress (τ, σ) and strain (γ, ϵ)



Normal Stress $\sigma = F\sin\theta/A$

Normal Strain $\epsilon = \delta/L$

Shear Stress $\tau = F\cos\theta/A$

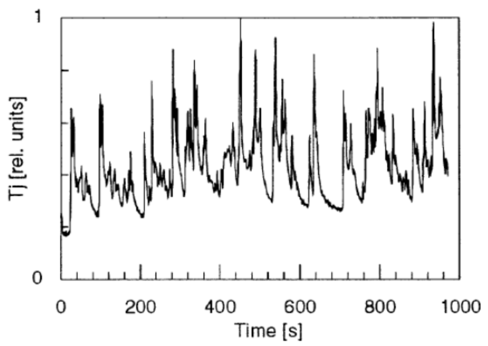
Shear Strain $\gamma = \Delta L/L$

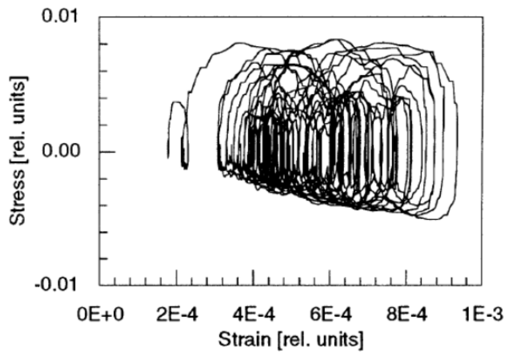
Physical Lifetime Modeling

$$N_f = f(\Delta\gamma), f(\Delta\tau), f(\Delta D), f(\Delta W)$$

$$\frac{da}{dN} = K_1(\Delta W)^{K_2} \qquad N_f = \frac{1}{2}\left[\frac{\Delta\gamma}{2\epsilon'_f}\right]^{1/c} \qquad \Delta W \cdot (N_f)^m = K$$

Parameterization of models?

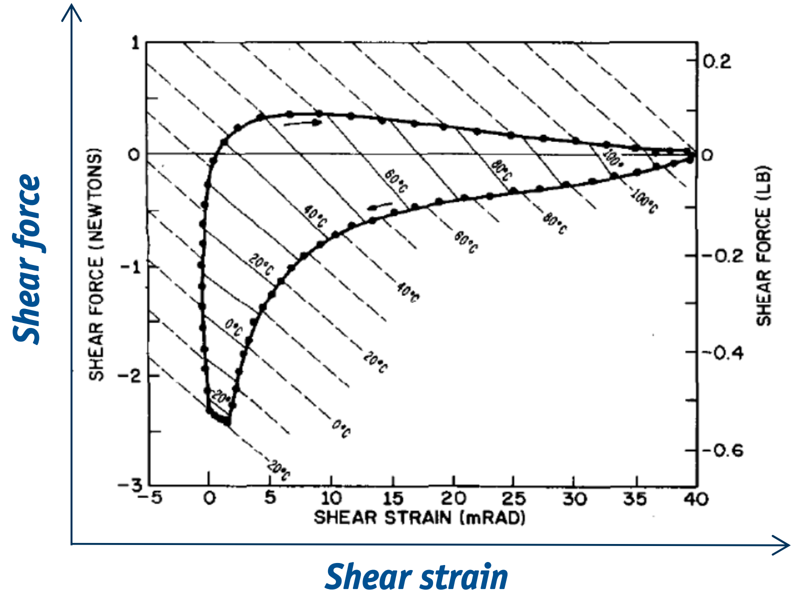




Ref [M. Ciappaet al., "Lifetime Prediction and Design of Reliability Tests for High-Power Devices in Automotive Applications"]

Stress-Strain Relation for Solder Joint

- How does stress appear and act within materials?
- Correlate stress/strain values with observed failures?
- Hysteresis: stress-strain response of solder joint to periodical temperature cycling



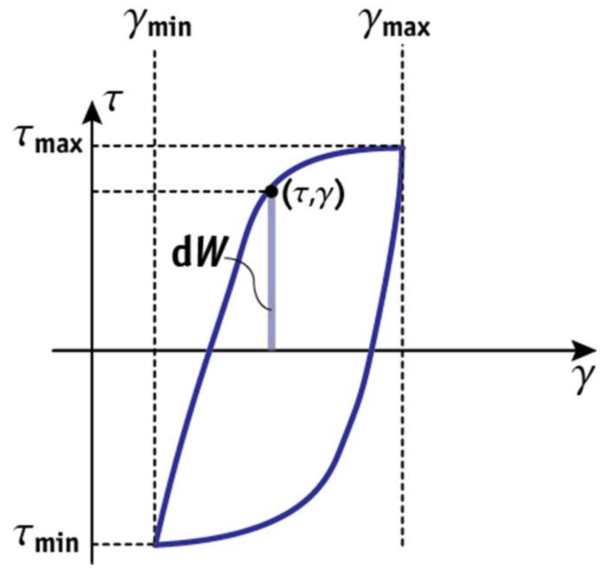
Ref [M. Hall, "Forces, moments, and displacements during thermal chamber cycling of leadless ceramic chip carriers soldered to printed boards"]

⇨ Energy based models $$\Delta W_{tot} = \int_{\gamma_{min}}^{\gamma_{max}} \tau d\gamma$$

Proposed Lifetime Modeling Approach

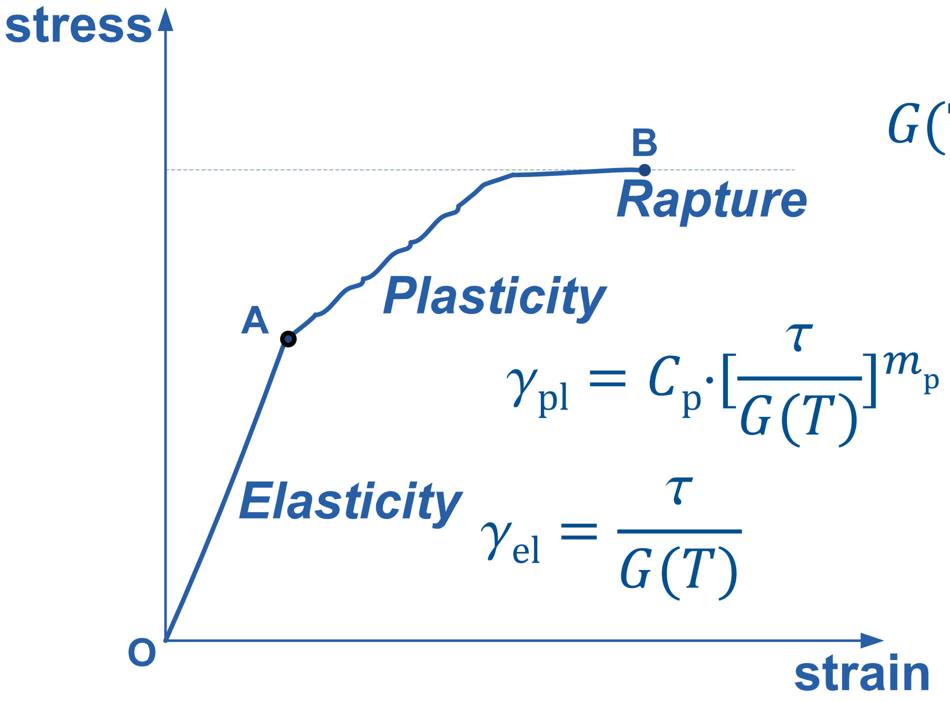
- **Main idea of energy-based models**
  - * ΔW_{acc}: Total deformation energy accumulated within module
  - * End-of-Life (EOL): device fails when deformation work ΔW_{acc} reaches critical value ΔW_{tot}
- **Clech's algorithm**
- **Constitutive solder equations**

$$\Delta \mathrm{W}_{\mathrm{acc}} = \int_{\gamma_{min}}^{\gamma_{max}} \tau d\gamma$$



Solder Physics – Equations (1)

- **Fatigue: elastic and plastic time-independent deformation**



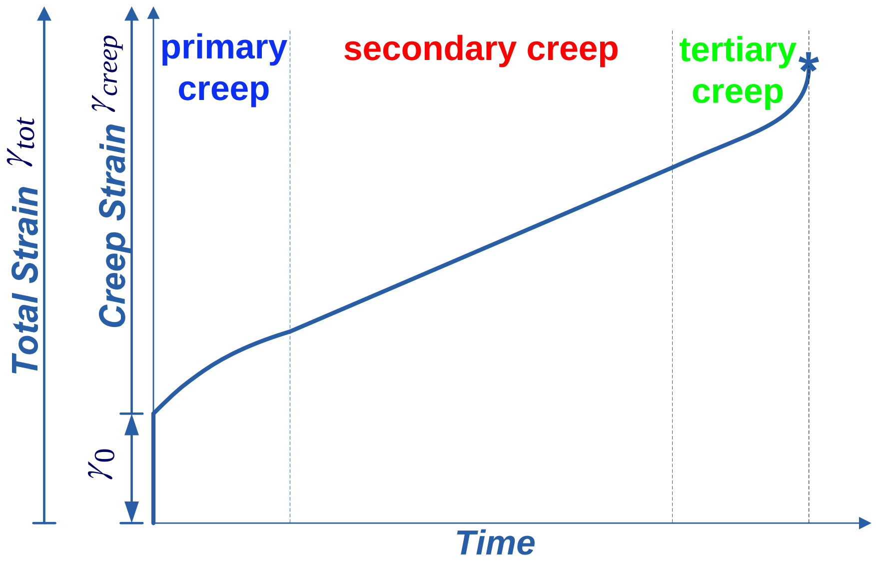
$$G(\mathrm{T}) = G_0 - G_1 \cdot (T - 273\mathrm{K})$$

$$\gamma_{\mathrm{pl}} = C_{\mathrm{p}} \cdot \left[\frac{\tau}{G(T)}\right]^{m_{\mathrm{p}}}$$

$$\gamma_{\mathrm{el}} = \frac{\tau}{G(T)}$$

Solder Physics – Equations (2)

- **Creep:** time-dependent **plastic deformation**



Sn37Pb

$$\dot{\gamma}_S = \frac{d\gamma_S}{dt} = B_1 \cdot \frac{G(T)}{T} \cdot \frac{\tau}{G(T)} \cdot e^{-Qb/RT} + B_2 \cdot \frac{G(T)}{T} \cdot \frac{\tau}{G(T)} \cdot e^{-Qm/RT}$$

$$\dot{\gamma}_S = \frac{d\gamma_S}{dt} = C_l \cdot \frac{G(T)}{T} \left[\sinh \frac{\alpha \cdot \tau}{G(T)}\right]^{n_l} \cdot e^{-Ql/RT} + C_h \cdot \frac{G(T)}{T} \left[\sinh \frac{\alpha \cdot \tau}{G(T)}\right]^{n_h} \cdot e^{-Qh/RT}$$

$$\dot{\gamma}_S = \frac{d\gamma_S}{dt} = C_1 \cdot \frac{G(T)}{T} \left[\sinh \frac{\alpha \cdot \tau}{G(T)}\right]^{n_l} \cdot e^{-Q/RT}$$

$$\dot{\gamma}_S = \frac{d\gamma_S}{dt} = A_1 \cdot \tau^{m_1} \cdot e^{-Qa_1/kT \cdot (1-\tau/\sigma_{01})} + A_2 \cdot \tau^{m_2} \cdot e^{-Qa_2/kT \cdot (1-\tau/\sigma_{02})}$$

Sn3.5Ag

$$\gamma_T = \gamma_t \cdot \frac{\tau}{G(T)} \cdot (1 - B \cdot \dot{\gamma}_S \cdot t)$$

- **Material parameters (alloy-dependent)**

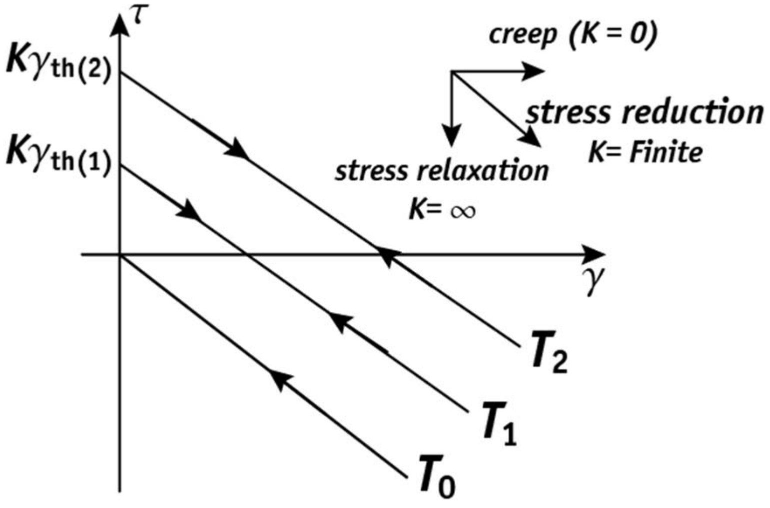
Stress-Reduction Lines of Solder Material

- Solder geometry properties: height-*h*, length-*L*, area-*A* of solder joint
- Geometry dependent parameters which has to be found:
  - Mechanical modeling of power module based on Finite Element Analysis
  - Optimization Approach

$$\gamma_{shear} + \frac{\tau_{shear}}{K} = D_1 \cdot (T - T_0)$$

$$K \approx \frac{h}{A}, D_1 \approx L\left(\frac{1}{CTE_1} - \frac{1}{CTE_2}\right)$$

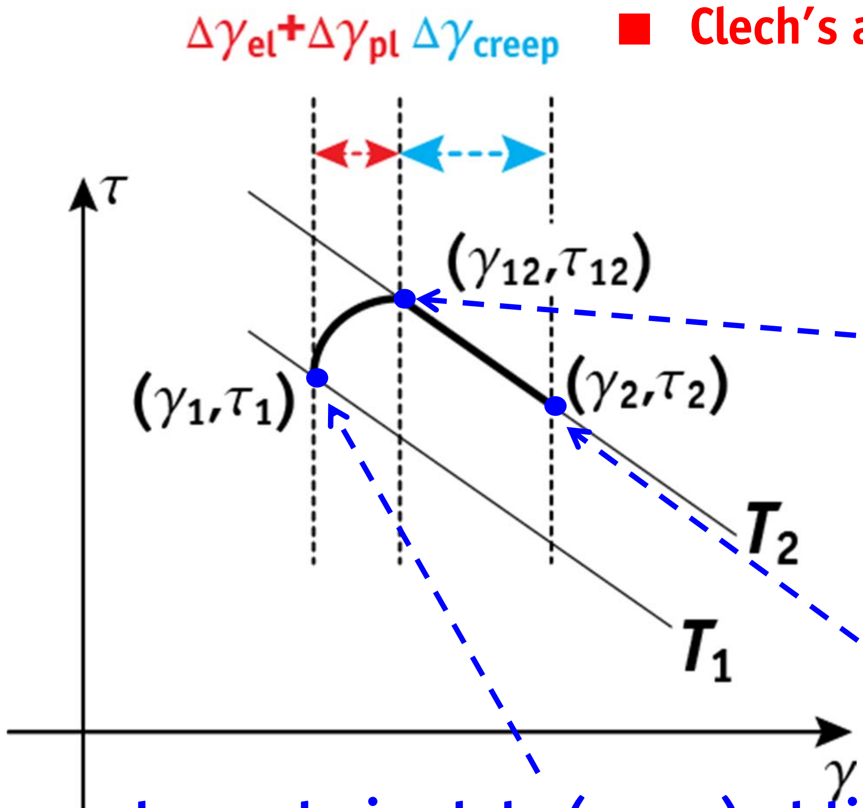
$$\tau = K(\gamma_{th}(T) - \gamma)$$



$$\gamma_{th}(T) = D_1(T - T_0)$$

Numerical Modeling of Stress-Strain

- **Clech's algorithm**



γ_1 - γ_{12} : **fast time-independent transient**

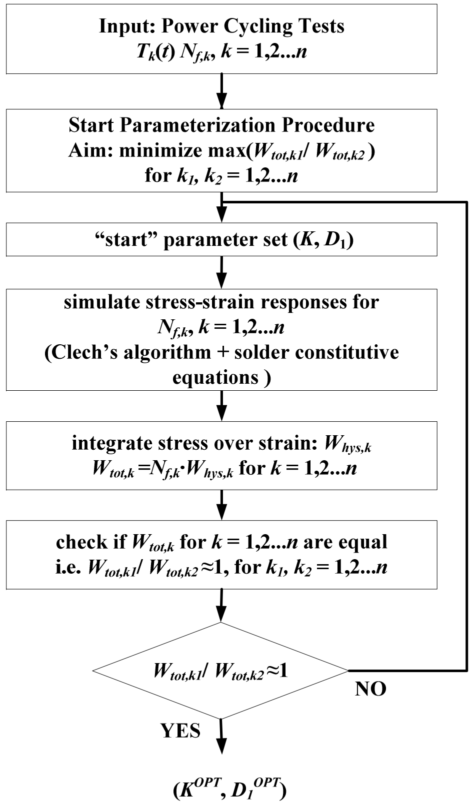
stress-strain state (γ_2, τ_2) at time $t + \Delta t$

stress-strain state (γ_1, τ_1) at time t

Lifetime Model Parameterization

- **Input: 3 PC Tests**
  $(T_1(t), N_{f1}), (T_2(t), N_{f2}), (T_3(t), N_{f3})$
- $W_{totk} = N_{fk}(W_{hysk})^m \ ,k = 1,2,3$
- **Exponent m depends on solder material**
- **Optimization routine is used to find best set (K, D_1) : $r_{ji} = \frac{W_{totj}}{W_{toti}} \approx 1$**
- **Relative Lifetime Estimation**

$$r = \frac{\int \tau_1 d\gamma_1}{\int \tau_2 d\gamma_2}$$



Input Data for Lifetime Estimation

- **Solder material data from Literature**

  X. Q. Shi et al., "Creep Behaviour and Deformation Mechanism Map of SnPb Sutectic Solder Alloy," 2003;

  J-P. Clech, "An obstacle controlled creep model for SnPb and Sn-based lead-free solders,"2004;

- **Power Cycling (PC) Data:**
  Temperature Profiles - $T_{solder}(t)$ & Number of Cycles to Failure - N_f
- **Solder geometry data:**

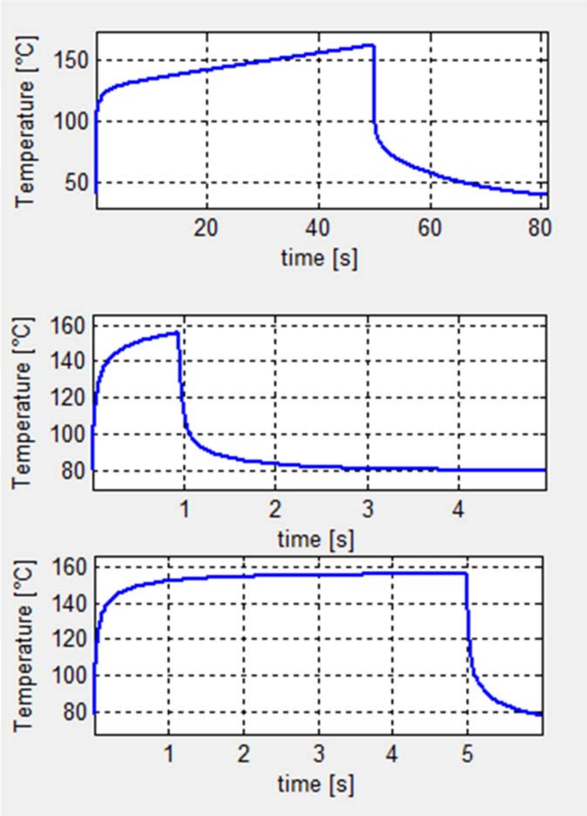
  First task: Parameterization of the proposed lifetime model to determine geometry solder parameters → Searching for optimal parameter set [K, D_1]

  Second task: Lifetime estimation for given PC and mission profiles

Verification based on PC Test Data

- PCs with solder (chip solder layer) failure as dominant failure mode
- PC Temperature Profiles: $T_{solder}(t)$ extracted based on thermal model of power module
- $[K, D_1]$ selected based on min parameterization error (for $m = 2.2$, $W_{totk} = N_{fk}(W_{hysk})^m$)
- PC 1-3 used for parameterization:
  PC1: $\Delta T = 115$ K, $T_{max} = 155°C$, $t_{on} = 50s$
  PC2: $\Delta T = 70$ K, $T_{max} = 150°C$, $t_{on} = 0.95s$
  PC3: $\Delta T = 70$ K, $T_{max} = 150°C$, $t_{on} = 5s$

PC1
PC2
PC3



Results for PC1-3

- Error of parameterization = 1.71

  W_{tot1}, W_{tot2}, W_{tot3} → (N_{fmin}, N_{fmax})

- N_{f1} = 31 332,

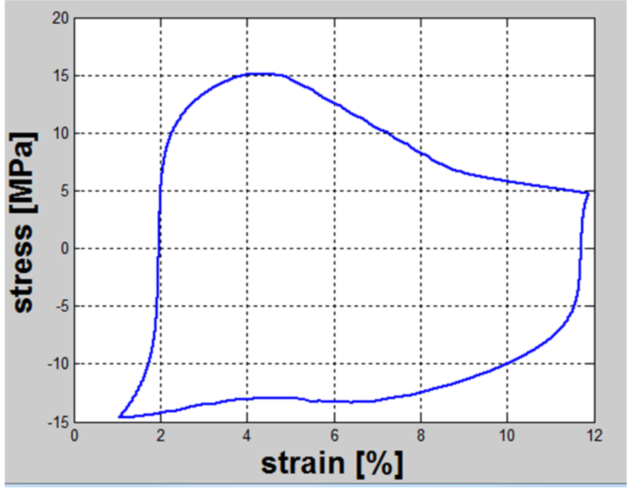
  N_{fcalc1} = (31 302, 38 762 , 53654)

  N_{f2} = 220 279

  N_{fcalc2} = (128 514, 159 142 , 220 279)

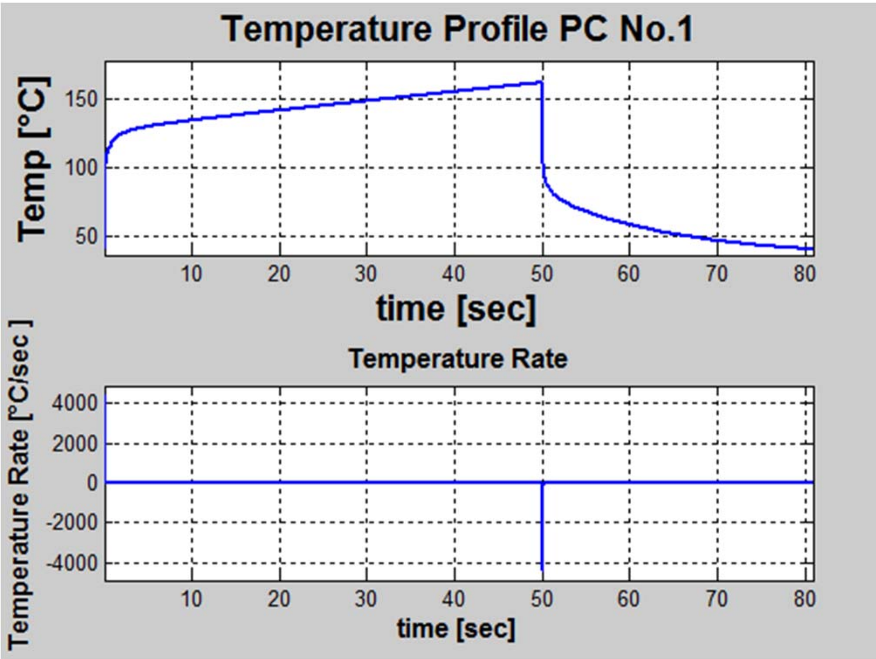
  N_{f3} = 168 390,

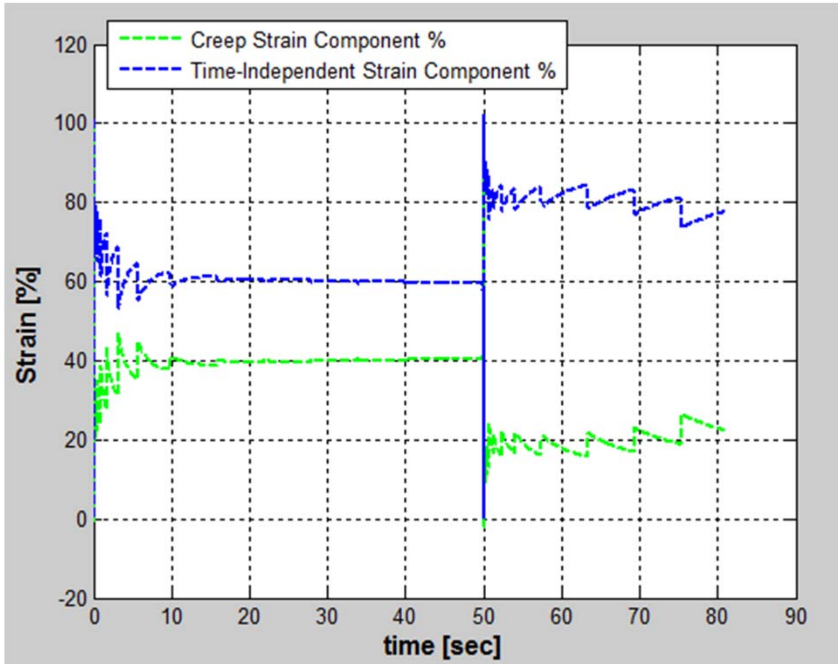
  N_{fcalc3} = (168 390, 208 521 , 288 627)



Results for PC1-3

- **Strain deformation under given *T*(*t*)**





Lifetime Estimation based on PC1-3

- **Verification for PC A-E**

PCA: ΔT = 134 K, T_{max} = 174°C, t_{on} = 64.5s
N_{fA} = 28 780, (23 216 – 28 749 – 39 793) δ_{max} =-19%

PCB: ΔT = 67 K, T_{max} = 146°C, t_{on} = 0.95s
N_{fB} = 248 710, (140 949 – 174 541 – 241 594) δ_{max} =-0.3%

PCC: ΔT = 70 K, T_{max} = 150°C, t_{on} = 1.2s
N_{fC} = 234 632, (122 054 – 151 142 – 209 205) δ_{max} =-10.8%

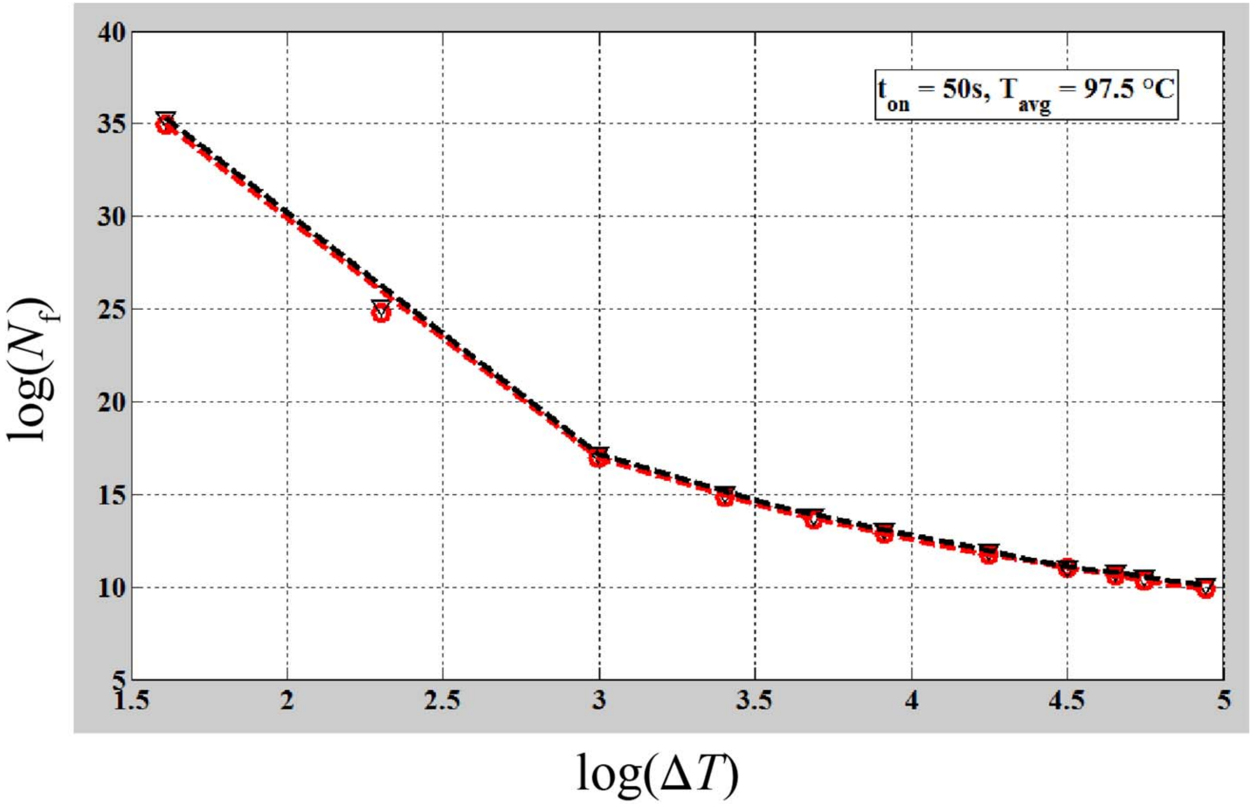
PCD: ΔT = 73K, T_{max} = 150°C, t_{on} = 2.9s
N_{fD} = 149 125, (164 966 – 204 281 – 282 758) δ_{max} =-9.6%

PCE: ΔT = 109K, T_{max} = 148°C, t_{on} = 13.6s
N_{fE} = 38 441, (31 393 – 38 875 – 53 809) δ_{max} =-18.3%

PCX: ΔT = 136K, T_{max} = 176°C, t_{on} = 2s
N_{fX} = 21 956, (21 853 – 27 061 – 37 457) δ_{max} =-23.5%

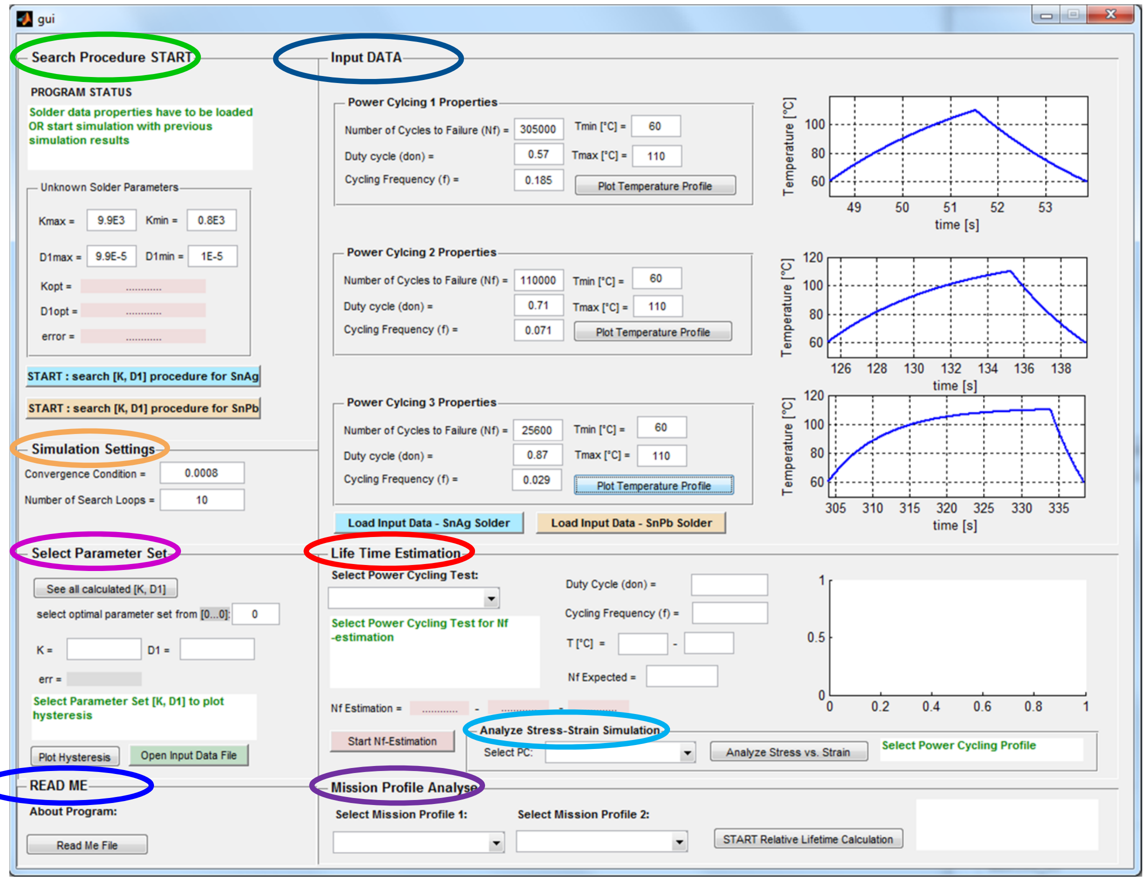
- Fast or slow temperature rate during T_{max} level determine strain development
- Longer pulse: stationary situation is reached, more deformation
- Parameter ΔT influence lifetime

N_f vs. ΔT Curves



MATLAB Graphical User Interface

- **MATLAB GUI Options**
  - *Search Parameters Procedure*
  - *Load Input Data*
  - *Set Simulation Settings*
  - *Modeling for selected [K, D_1]*
  - *PC Lifetime Estimation*
  - *Analyze Stress-Strain Response*
  - *Rel. Lifetime Calculation*
  - *Readme File*



Thank You !