Thermal Fatigue Life in μBGA and Flip Chip Solder Joints

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■ Education

1988 – 1992 : Faculty of Engineering,University of Osaka,Japan
Awarded the degree of PhD in Welding Engineering

■ Research and professional experience

1985 – 1987 : Researcher of Mechanical Technical Center,
Daewoo Heavy Industry Incheon, Korea.
1992 – 1994 : Principal Researcher of Packaging Team,
Semiconductor Technical Center,
Samsung Electronics Co.,Ltd.Kihung,Korea.
1994 – 1997 : Assistant Professor of Department of Mechanical
Engineering Chung-Ang University, Seoul,Korea.
2001 - Present : Chair Professor of Department of Mechanical
Engineering Chung-Ang University,Seoul,Korea

Research Fields

1. Micro soldering processes – Wave Type

- Reflow Type(IR, Hot Air)
- Pulse Heat Tool Type
- Electric Resistance Type

2. Evaluation of Micro Joints

- Thermal Fatigue
- Life Prediction
- Aging Characteristic
- Migration
- Whiskers

3. Electronic packaging Processes

- Plating
- Wire Bonding
- TAB
- BGA

4. Development and design of new materials

- Lead Frame
- Solder Ball
- Under fill
- Lead Free Solder Paste

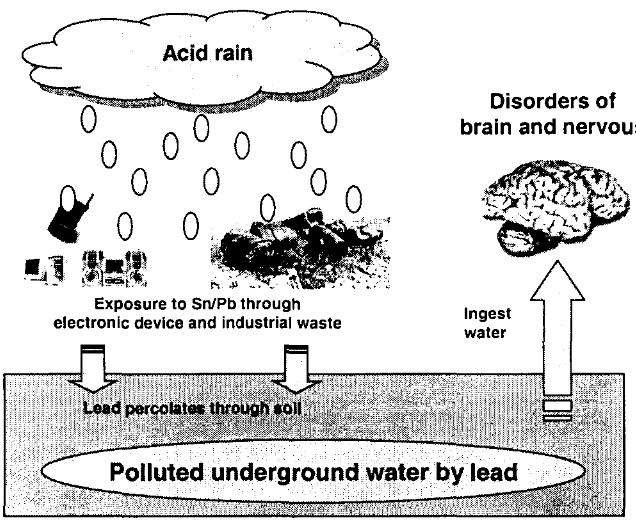
중앙대학교

The Thermal Fatigue life of Lead-Free Solders in Micro BGA Solder Joints

Chung-Ang University

Young-Eui Shin

Problems of Lead in the Environment



Requirements for Lead-free Solder

Solderability & Low cost

Low melting Temperature 456K:Sn37Pb

Lead free solder

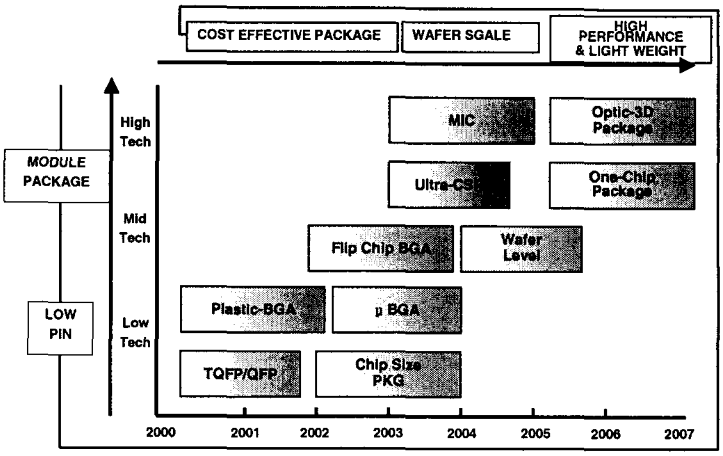
No toxicity & health hazard

Long term reliability

Compatible Lead-free Solder (T_m>479K)

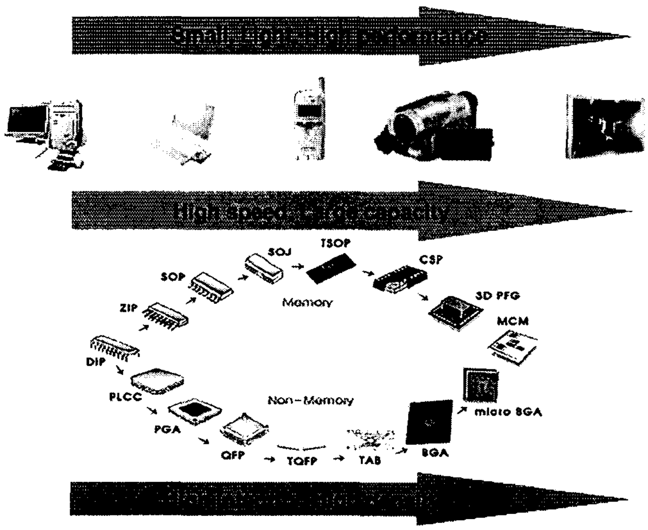
Alloy system	Company	Composition(mass%)
Sn-Ag	NEC (Japan)	Sn-3.5Ag-0.7Cu(Sn-3.5Ag(Mp:494K))
	Oki (Japan)	Sn-3.5Ag(-0.7Cu)
	Iowa State Univ. (USA)	Sn-4.7Ag-1.7Cu
	AIM Inc. (USA)	Sn-2.5Ag-0.8Cu-0.5Sb
Sn-Ag-Bi	Hitachi (Japan)	Sn-Ag-Bi(ex. Sn-2.5Ag-2.0Bi)
	Sony (Japan)	Sn-2Ag-4Bi-3.0In-0.1Ge
	Sandia National Lab. (USA)	Sn-3.4Ag-4.8Bi
	Cookson Technol. C. (USA)	Sn-2Ag-7.5Bi-3.0In
Sn-Ag-Bi-In	Matushita (Japan)	Sn-Ag-Bi-In (Sn-2.5Ag-2Bi-3In)
	Toyata (Japan)	Sn-2.5Ag-3Bi-1In-0.2Cu
	Mitsui (Japan)	Sn-2.5Ag-2.5Bi-2.5In
Sn-Zn	Toshiba (Japan)	Sn-8.8Zn(T_m:472K)
Sn-Cu	IEC electronics corp. (USA)	Sn-0.7Cu (T_m:493K)
	Matushita (Japan)	Sn-0.7Cu-X
Sn-Bi	Fujitsu (Japan)	Sn-58Bi (T_m:412K)

Package Technology



Introduction

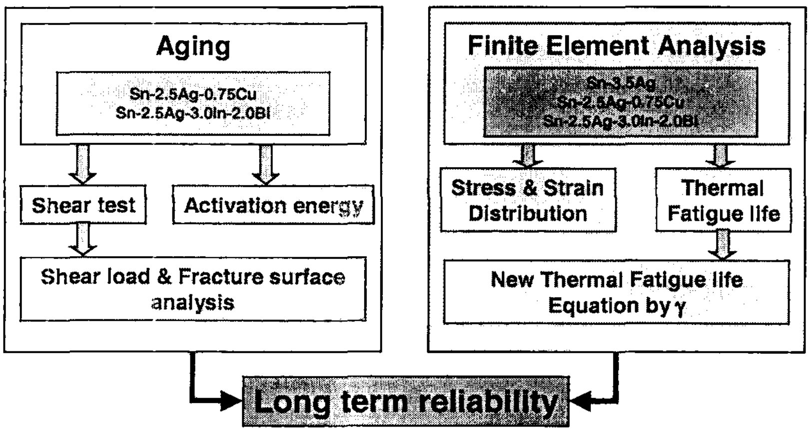
Package Trends



Content 1

Solder joint Fatigue Models & FE Analysis Procedure

Approach method of Aging & Thermal Fatigue Life



Thermal Fatigue Life Evaluation

Von-mises yield condition equation

$$\sigma_{eq} = \frac{1}{\sqrt{2}}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]^{1/2}$$

$$\varepsilon_{eq} = \frac{\sqrt{2}}{3}\left[(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_3-\varepsilon_1)^2\right]^{1/2}$$

Total equivalent strain

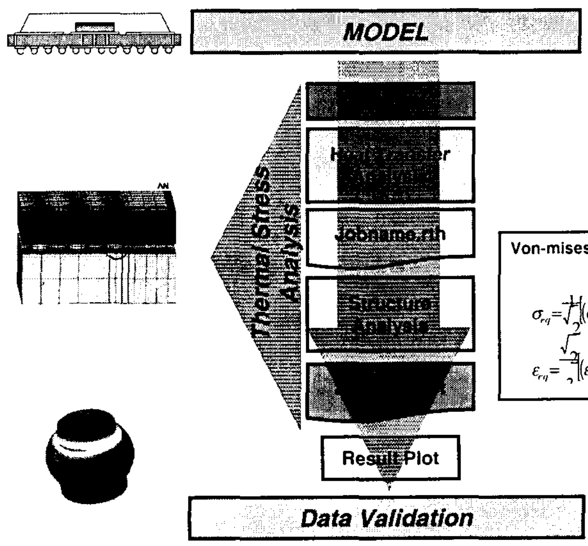
$$\varepsilon_t = \varepsilon_{el} + \ldots$$

$\Rightarrow N_f$

Fatigue constant(C) and Fatigue exponent(α) of four different solder alloy

	Sn-37Pb	Sn-3.5Ag	Sn-2.5Ag-0.7Cu	Sn-2.5Ag-3.0In-2.0Bi
C	0.24	0.90	0.56	0.45
α	0.49	0.6	0.53	0.51

Finite Element Analysis Procedure



Von-mises yield condition equation

$$\sigma_{eq} = \frac{1}{\sqrt{2}}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]^{1/2}$$

$$\varepsilon_{eq} = \frac{\sqrt{2}}{3}\left[(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_3-\varepsilon_1)^2\right]^{1/2}$$

Solder Joint Fatigue Models

Fatigue Models	Model Class	Required Parameters	Coverage
Coffin-Manson	Plastic strain fatigue model	Plastic strain	Low cycle fatigue
Coffin-Manson-Basquin	Plastic strain fatigue model	Plastic strain + Elastic strain	High and low cycle fatigue
Solomon	Plastic strain fatigue model	Plastic shear strain	Low cycle fatigue
Engelmaier	Plastic strain fatigue model	Total shear strain	Low cycle fatigue
Shin	Plastic strain fatigue model	Plastic strain	Low cycle fatigue
Knecht and Fox	Creep strain fatigue model	Matrix creep shear strain	Matrix creep only
Darveaux	Energy based model	Damage + energy	Hysteresis curve

Characteristics of Each Fatigue Model

Plastic strain based fatigue model

Coffin–Manson
- Best known & Most widely used approach
- Only considers plastic deformations

Coffin–Manson–Basquin
- Total strain which also covers elastic deformation

Solomon
- Plastic shear strain range unlike Coffin-Manson equation (Plastic stain amplitude)
- Doesn't account for creep behavior → limitation in its practical use for solder joints

Engelmaier
- Total shear strain with cyclic frequency and temperature
- Based on isothermal experimental fatigue data → limited in application to new model

Shin
- Plastic strain amplitude with temperature dependent factor γ
- Doesn't account for creep behavior

Creep Strain based fatigue model

Knecht & Fox
- Simple matrix creep fatigue model (Only considers dislocation movement of solder)
- *Doesn't account for grain boundary creep*

Energy based fatigue model

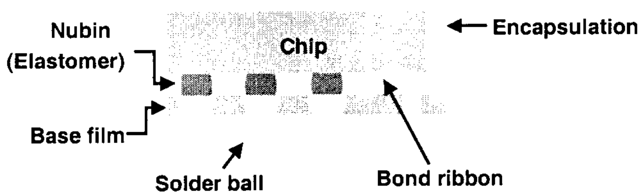
Dasgupta
- Total strain energy → Good indicator of solder joint damage

Darveaux
- Incorporates crack propagation (overcomes limitation of previous energy-based model)
- Include energy density term from stress-strain hysteresis curve

Content 2

Experimental & Theoretical Thermal Fatigue Life Evaluation of μBGA

48 μBGA Package



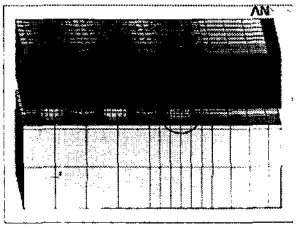
Package profile

- Ball count : 48 (6×8)
- Body size : 6.3×6.2mm
- Ball size & pitch : 0.35mm, 0.75mm
- Base film thickness : 50μm
- Chip thickness : 0.43mm
- Cu(Au) thickness : 18(1.0±0.3)μm

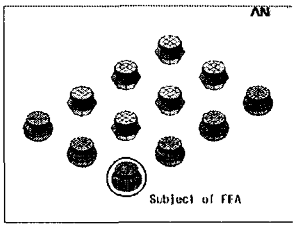
Application

- Memory card & devices
- SRAM, DRAM, FLASH
- Laptop PCs, Hard Drives
- Camcorders, Cellular Phones

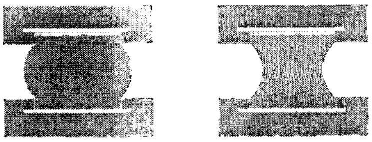
Finite Element Modeling of 48 μBGA



(a) Full shape after modeling

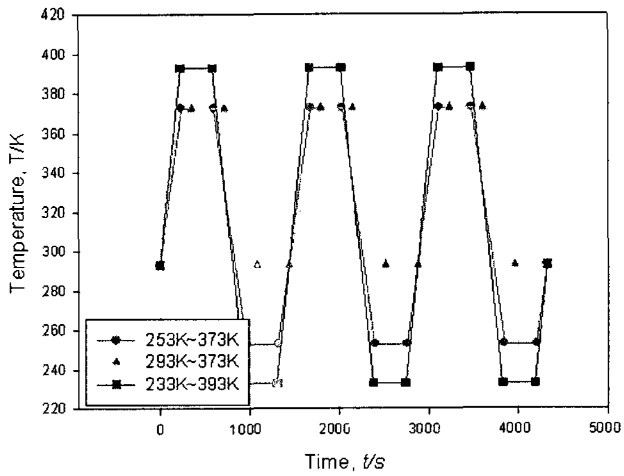


(b) Solder joints



(c) Solder ball shapes

Temperature Profile for TC Test



Mechanical Properties of Components

		Density (ρ:kg/mm^3)	Elastic Modulus (E:Gpa)	Coefficient Thermal Expansion (CTE :ppm)	Poisson's Ratio (v)
Si chip		2.33E-6	188	23	0.25
Encapsulant		1.77 E-6	2.54	164	0.4
Elastomer		1.03 E-6	0.25	220	0.45
Cu pad		8.92 E-6	119	17	0.343
Base film		1.6 E-6	4	17	0.35
Solder	Sn-Pb	8.42 E-6	25.8	21.4	0.4
	Sn-Ag	7.36 E-6	43.2	30	0.3
	Sn-Ag-Cu	7.4 E-6	45.1	23	0.3
	Sn-Ag-In-Bi	7.3 E-6	42.0	25	0.3
PCB		1.03	0.25	220	0.45

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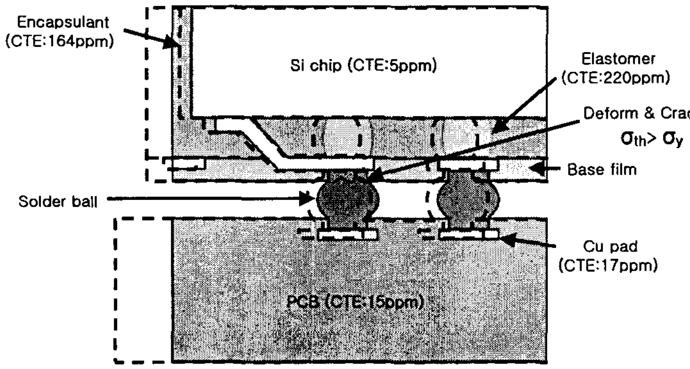
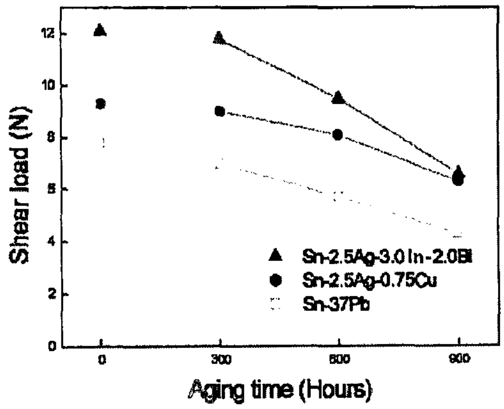
Thermal Fatigue Failure at Solder Joints



Thermal stress concentration mechanism

Shear Load



Relation between aging time and shear load with solder alloys at aging temperature 170℃

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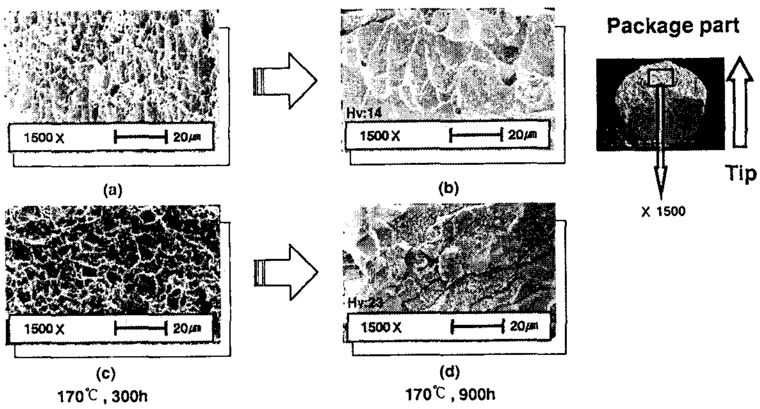
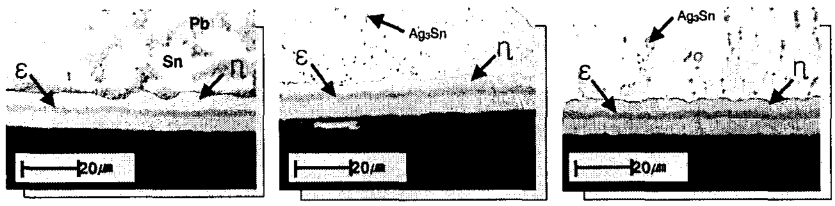
Fracture Surface after Shear Test



Fracture surface of Sn-Ag-Cu(a,b) and Sn-Ag-In-Bi(c,d)

Intermetallic Compound Layers

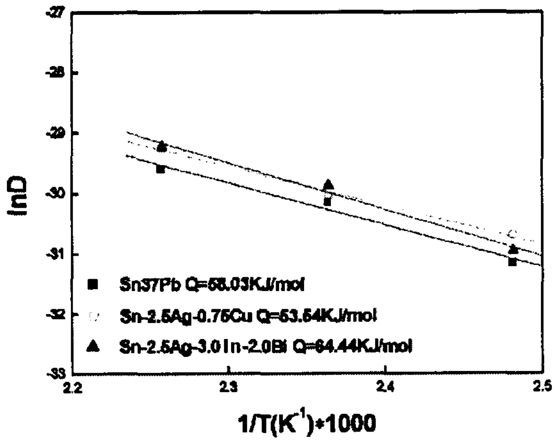
Sn-37Pb Sn-2.5Ag-0.75Cu Sn-2.5Ag-3.0In-2.0Bi



ε : Cu_3Sn η : Cu_6Sn_5

Phases of the intermetallic compound layer by aging(170℃, 900h)

Activation Energy of Sn-Pb and Lead-free Solders



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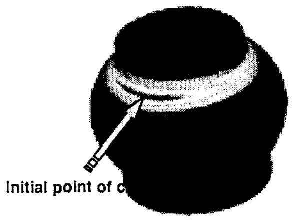
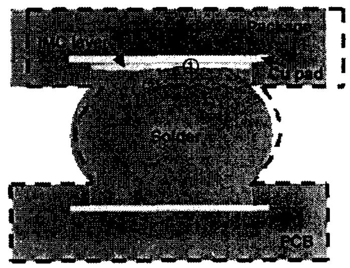
Stress Concentration Area and Crack Growth Mode





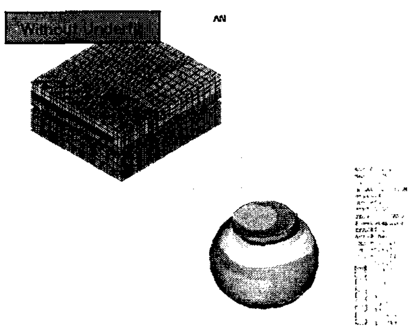
Mode 1 : Interface fracture of solder and IMC layer
Mode 2 : Solder inside fracture

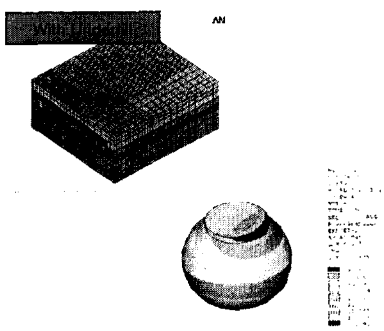
(a) FEA results for effective to the thermal cycling

(b) Growth mode of the crack

Content 2

Stress Distribution & Theoretical Results by Engelmaier's Fatigue Model

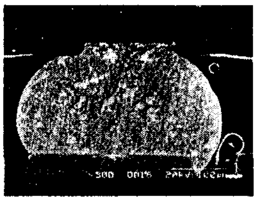


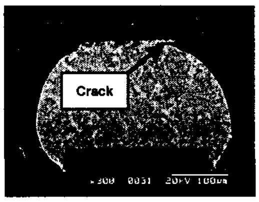


	Without underfill	With underfill
$\Delta\varepsilon^{p}_{eq}$ (%)	1.5212	0.5353
$\Delta\varepsilon^{c}_{eq}$ (%)	1.5664	0.5796
$\Delta\gamma^{t}_{eq}$ (%)	2.7131	1.0038
N_f	1405	16873

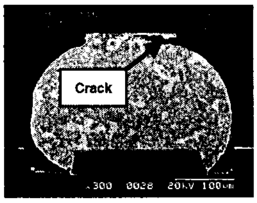
Content 2

Cross Sectional View of Solder Joint without Underfill (ΔK: 160K)

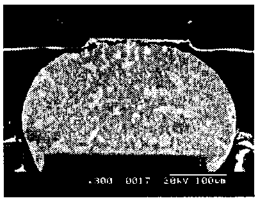

(a) After 500 cycles



(b) After 600 cycles



(c) After 700 cycles


(d) After 800 cycles

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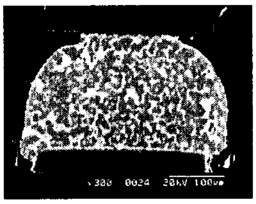
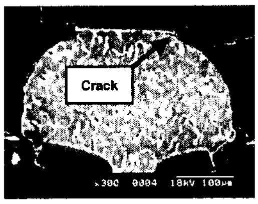
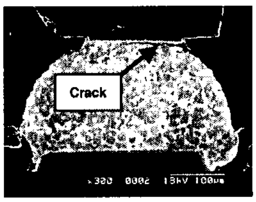
Cross Sectional View of Solder Joint with Underfill (ΔK: 160K)

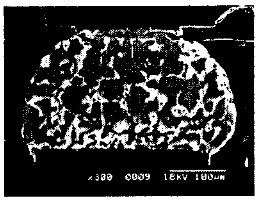

(a) After 4500 cycles



(b) After 5000 cycles

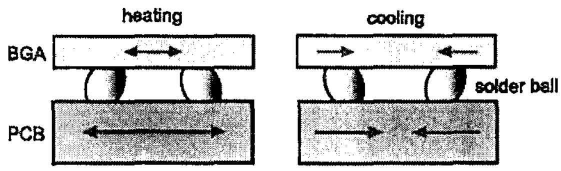


(c) After 5500 cycles

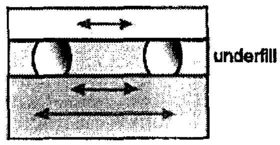

(d) After 6000 cycles

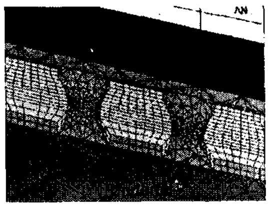
Failure Mechanism of Solder Ball with Underfill

Thermomechanical deformation without underfill



Thermomechanical deformation with underfill



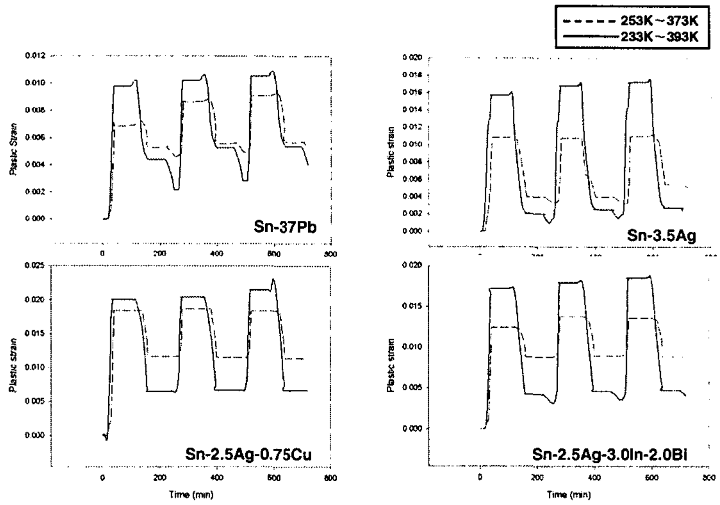


Mean Elastic-Plastic Strain Amplitude under Various Conditions

T_{cycle}(K)			Sn-37Pb	Sn-3.5Ag	Sn-2.5Ag-0.75Cu	Sn-2.5Ag-3.0In-2.0Bi
$\Delta\varepsilon_{el}$	293~373		0.000592	0.000267	0.000347	0.000303
	253 ~ 373	30°	0.000799	0.000248	0.000427	0.000317
		50°	0.000599	0.000209	0.000321	0.000257
		70°	0.000718	0.000332	0.000372	0.000383
	233 ~393		0.000915	0.000381	0.000489	0.000483
$\Delta\varepsilon_{pl}$	293~373		0.004766	0.003626	0.003713	0.000848
	253 ~ 373	30°	0.012684	0.004778	0.008242	0.007859
		50°	0.009675	0.002363	0.004996	0.004945
		70°	0.014836	0.005347	0.008377	0.008768
	233 ~393		0.015847	0.014668	0.014786	0.015806

Content 2

Strain Hysteresis Curves by Solder Alloy



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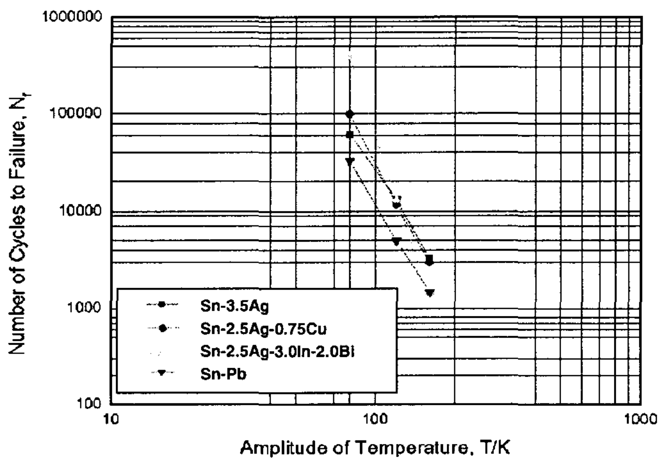
Correlation of log ΔT vs log N_f



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Temperature Dependent Dimensionless Factor γ

$$\gamma = \frac{\Delta T \cdot T_{mean}}{\frac{1}{2} T_M \cdot T_0}$$

ΔT: difference of temperature

$T_{mean}(K)$: mean temperature of thermal cycle

$T_M(K)$: melting point

$T_0(K)$: Reference temperature of thermal expansion

$$N_f = 10^{\log A + \beta \log \gamma}$$

$$N_f = A(\gamma)^{\beta}$$

A: Fatigue material constant

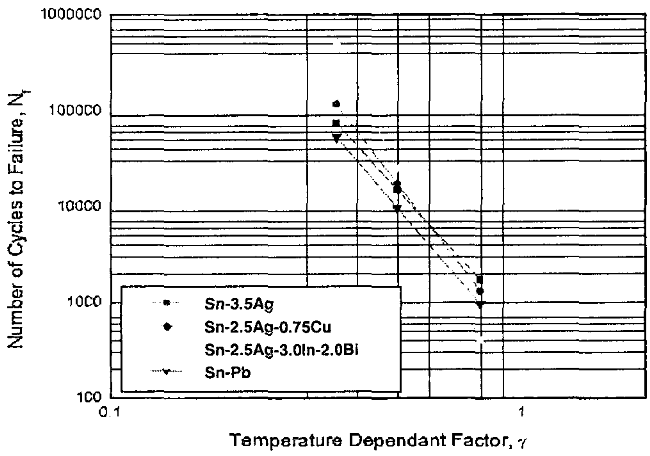
β: Fatigue material exponent

Calculated fatigue constant of various solder with γ

	Sn-37Pb	Sn-3.5Ag	Sn-2.5Ag-0.75Cu	Sn-2.5Ag-3.0In-2.0Bi
logA	2.492	2.774	2.565	1.716
β	- 4.967	- 4.660	- 5.561	- 8.887

Content 2

Log-log Graph of γ vs Nf



Conclusion. 1

1) Sn-Ag base solder alloys could be expected that the initial crack formation is more difficult because of a little change of the structure by aging and TC test compared to that of Sn-Pb solders.

2) The thermal fatigue life equation is derived using the dimensionless variable γ obtained from ΔT, T_m, T_{mean} for life evaluation of μBGA. In addition, the results with γ show a better linearity than using only ΔT.

3) At low temperature range from 293K to 373K, Sn-2.5Ag- 3.0In-2.0Bi shows the longest fatigue life. Moreover, at the temperature range from 233K to 393K, Sn-3.5Ag shows the longest fatigue life.

Conclusion. 2

Future Trends of Micro Joining

- The Joining Reaction Layer Control Technology
- The Joining Interface Analysis Technology
- Low Temperature Joining Technology
- New Materials Development
- The Establishment of Evaluation Technology