Fulcrum of Innovation: From Chemistry to Metallurgy

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TestConX™

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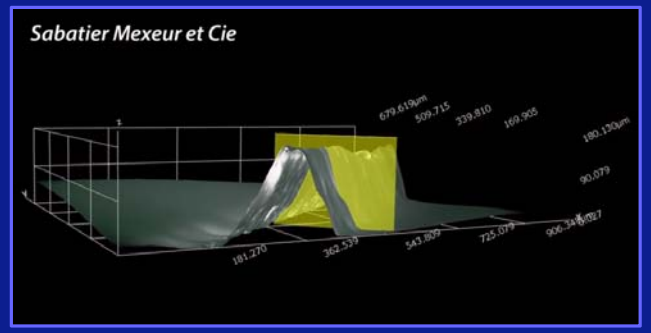
INDIUM CORPORATION®

- "Knives that would not cut"
- 7,000 year history of solder
- Solder in the 21st century
- Sintering innovations
- Metallic powder system innovations
- Solid metal preform innovations
- Liquid metal innovations
- Major drivers of innovation
- Hedgehogs and foxes

"Knives That Would Not Cut"

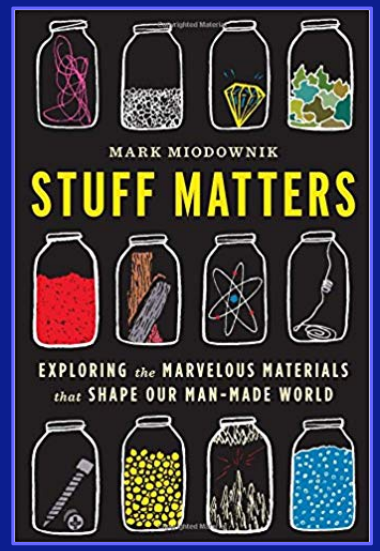
Source: www.AllenBrothers.com used with permission.



Source: America's Test Kitchen

Lessons from Stainless Steel

- Exploratory
- Iterative – many contributors
- Small science (vs. big science)
- Non-linear
- Careful observation
- Failures = Opportunities
- Trade-offs



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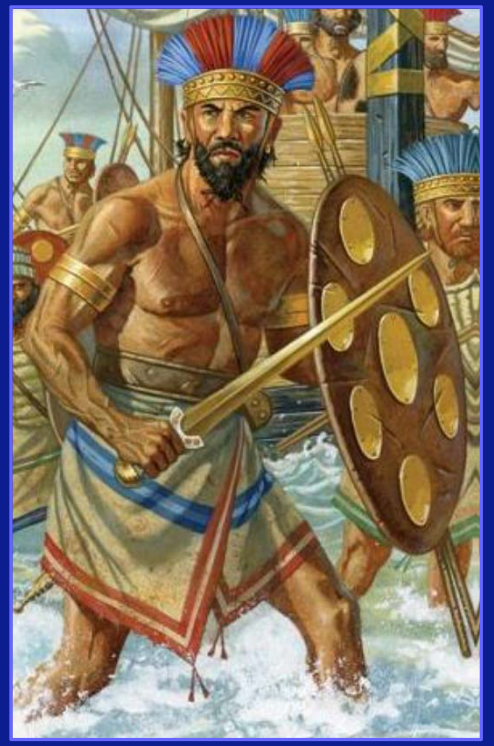
7,000 Years

- First solders introduced in Mesopotamia and Egypt
- Hard solders (Electrum: AuAg from joining the metals)
- Used for jewelry and weapon making
- Librarian at Goldsmith's puts soldering as beginning in 2600-2800 B.C.E.



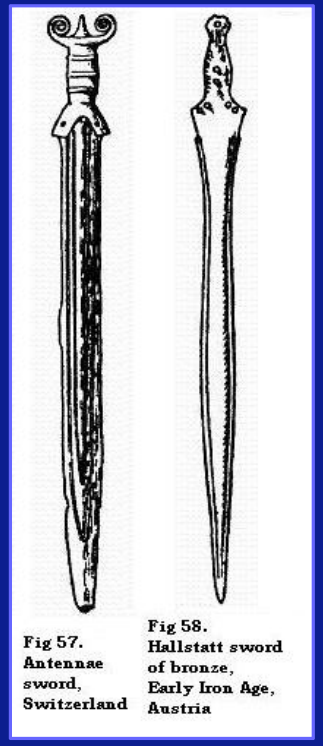


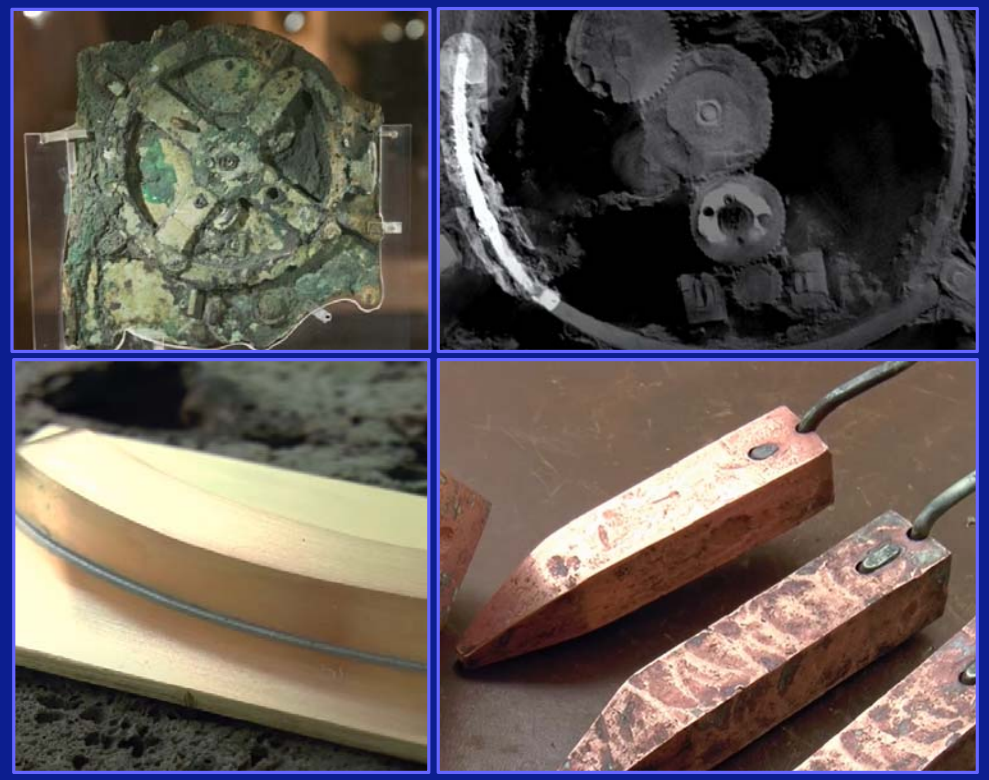
Fig 57. Antennae sword, Switzerland

Fig 58. Hallstatt sword of bronze, Early Iron Age, Austria

Source: K. Gilleo, "The First 7000 Years of Soldering, Part 1," Circuits Assembly, June 1995.
Craig Hillman DfR Monthly Webinars Feb 24, 2016
Librarian at Goldsmiths with reference to Encyclopedia Britannica

Antikythera Mechanism

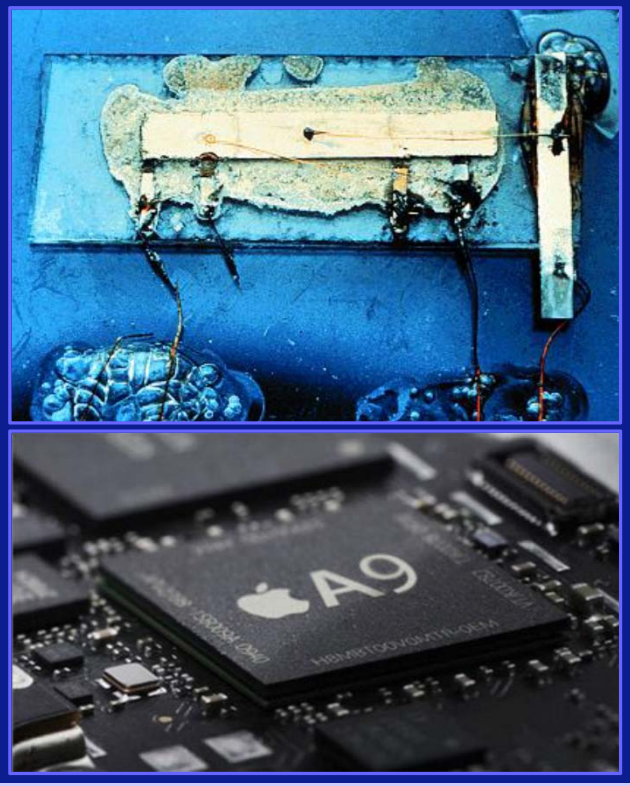
- Time period: 205? to 70? BC
- Pins and soft solder used to assemble
- Process: apply flux, then soft solder wire
- Heated copper “soldering blocks”
- Flux – likely rosin (colophony)
- Solder was likely 67Pb/33Sn



Source: https://en.wikipedia.org/wiki/Antikythera_mechanism; https://www.youtube.com/watch?v=T_MdxdGr57k

SnPb Solder is Forgiving

- Why SnPb solders? Why Not?
  - Relatively cheap
  - Electrically and thermally conductive
  - Wets (flows) really well
  - Tin bonds to most common metal (copper, nickel, zinc, gold, silver, iron, and aluminum)
  - Reliable (malleable, ductile, etc.)
  - Accommodates wide tolerances
  - Relatively low melting (183°C)
  - A true eutectic material



Source: Craig Hillman DfR Monthly Webinars Feb 24, 2016
John H. Lau, Ning-Cheng Lee: Assembly and Reliability of Lead-Free Solder Joints

1997 in Ireland

- Indium Corporation launched:
  - Five (5)
  - NEW
  - Breakthrough Products

All were SnPb!

- "Knives that would not cut"
- 7,000 year history of solder
- **Solder in the 21st century**
- Sintering innovations
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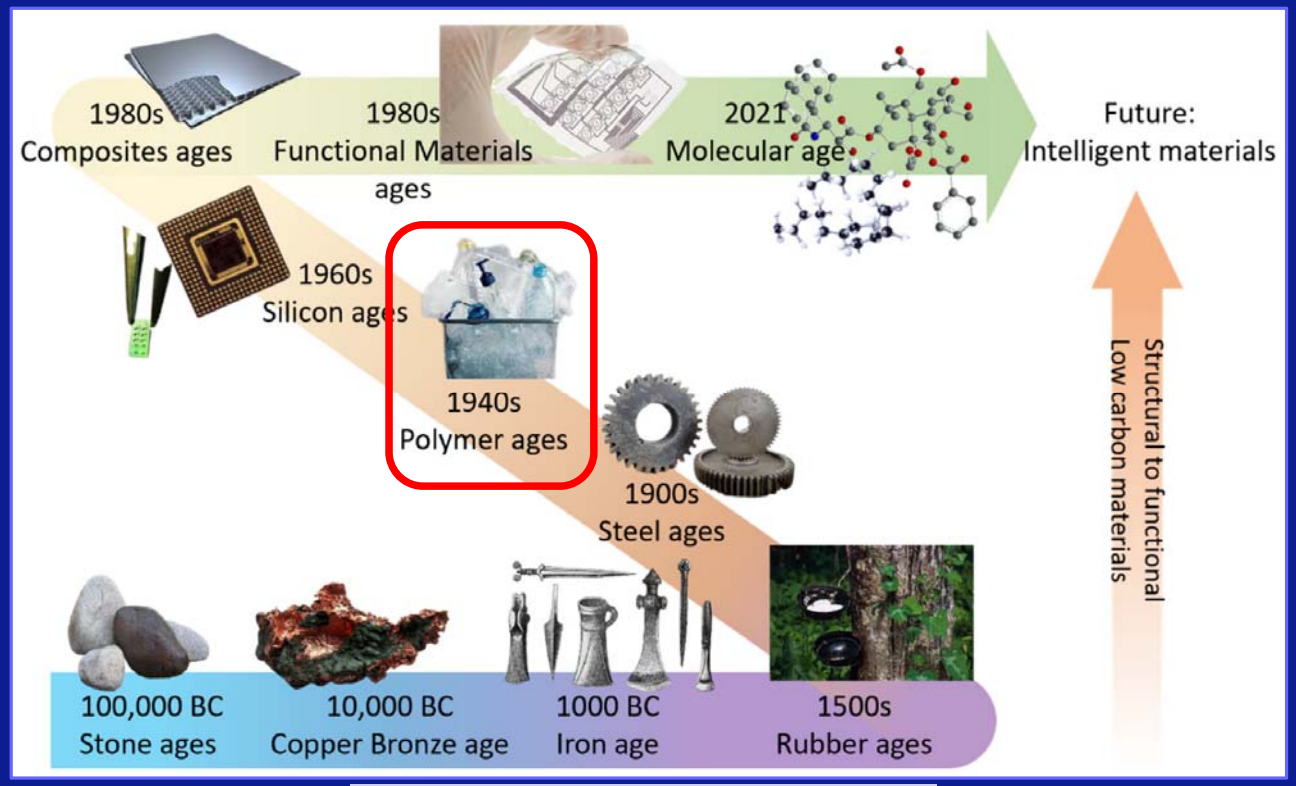
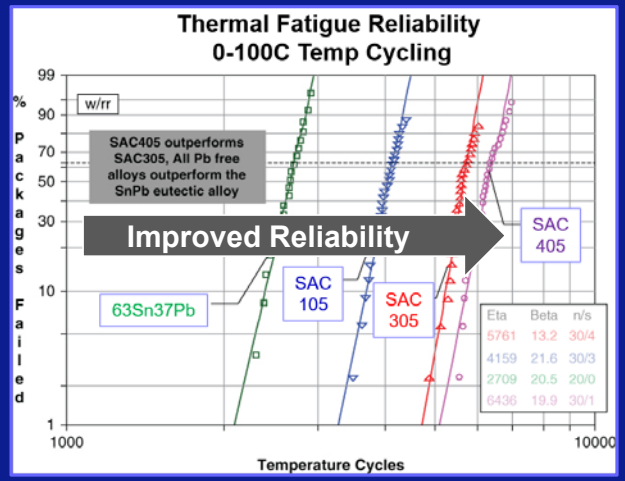
What Changed?



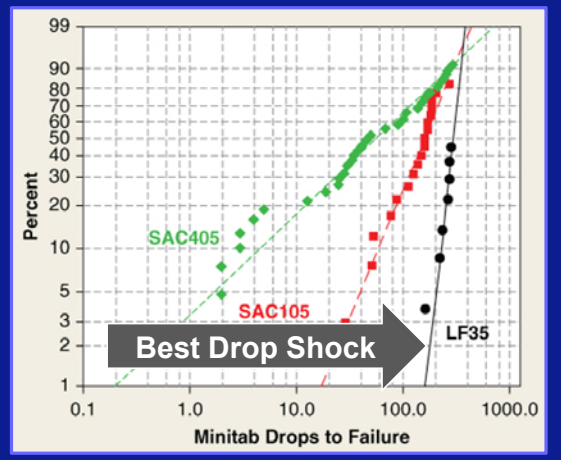
Source: Li Jingcheng, Intelligent Polymers, Fibers and Applications

1st Generation Lead-Free Solder SAC: SnAgCu

- July 1, 2006: WEEE Initiative:
  - All electronic assemblers selling products in Europe must be ready to convert to Pb-free
- Rapid convergence on one alloy family: SAC
- Higher Ag → Better thermal fatigue resistance
- Lower Ag → Better drop shock



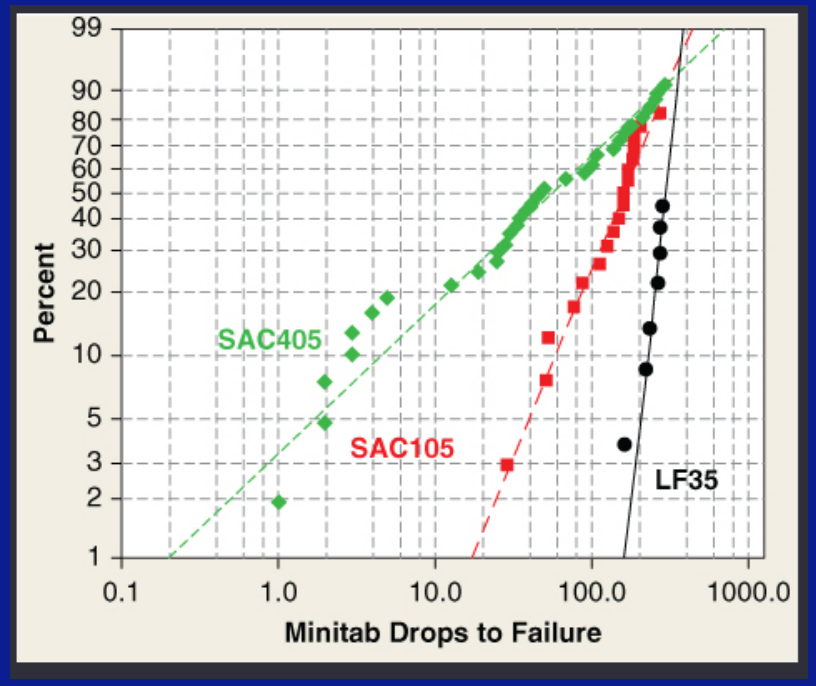
G. Henshall, et al, Proceedings of IPC APEX, 2009, S05-03



D. Kim, et al, Proceeding of 57th ECTC, 2007, P1614~1619

2nd Generation Lead-Free Solders

- Low Ag SAC increases the drop shock life but compromises the thermal fatigue reliability
- Low Ag had the added benefit of lower costs
- Compromises were necessary on thermal cycling reliability
- **Dopants** were added to mitigate tradeoffs with good marketing but had more questionable technical effects



D. Kim, et al, Proceeding of 57th ECTC, 2007, P1614~1619

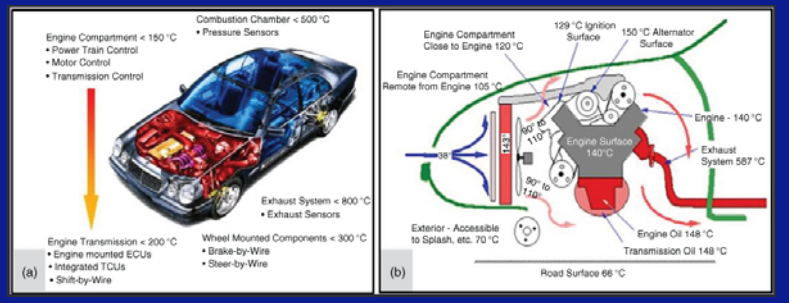
2006 to 2016

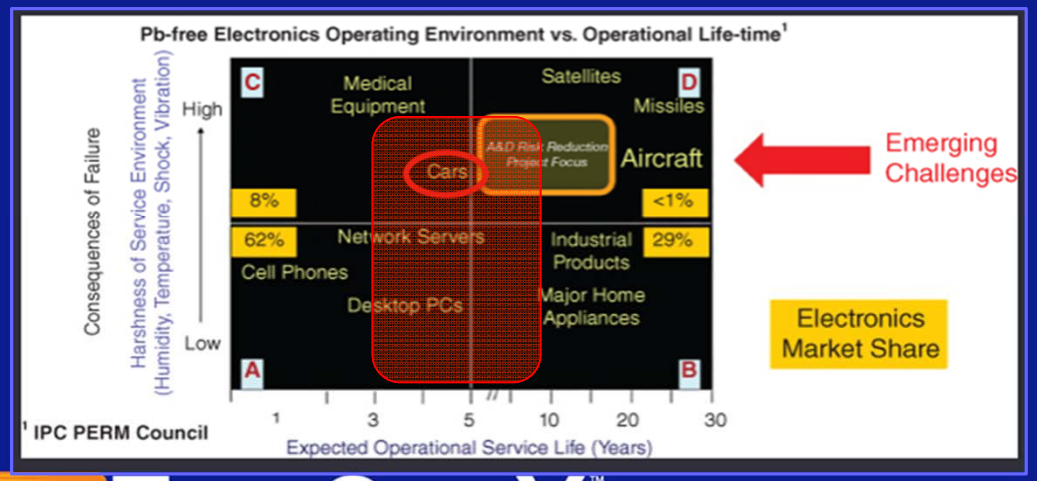
SAC Dominated
but limits began to Emerge

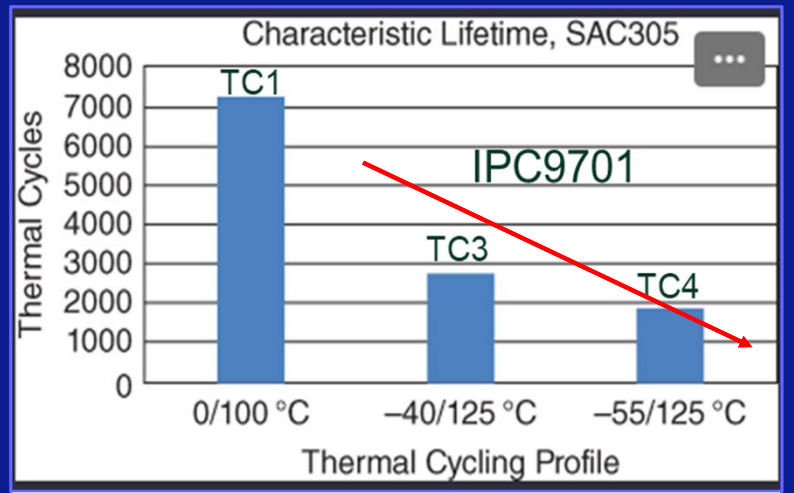
3rd Generation Lead-Free Solders

Automotive Electronics as Driver:

- Service life to 300,000km (186,000miles)
- Drive to zero failures (<<1ppb rate)
- Automotive may require temp cycling -40 to +175˚C (Grade 0++)
- SAC305 may not survive a longer service life under harsh conditions







Ch 7: Lead-free solders for high reliability and high performance applications, by Richard Coyle, in Lead-free Soldering Process Development and Reliability, Edited by Jasbir Bath, Wiley 2020

3rd Generation Lead-Free Solders

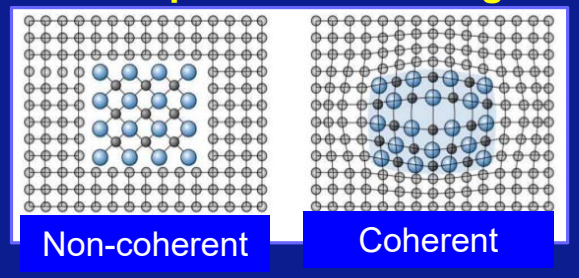
Reinforcement of Sn-rich solder

The first commercial, third generation LF solder

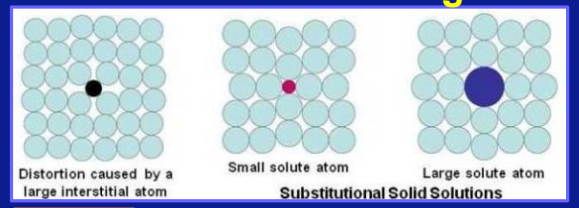
Innolot®: SAC387+3%Bi+1.5%Sb+0.15%Ni

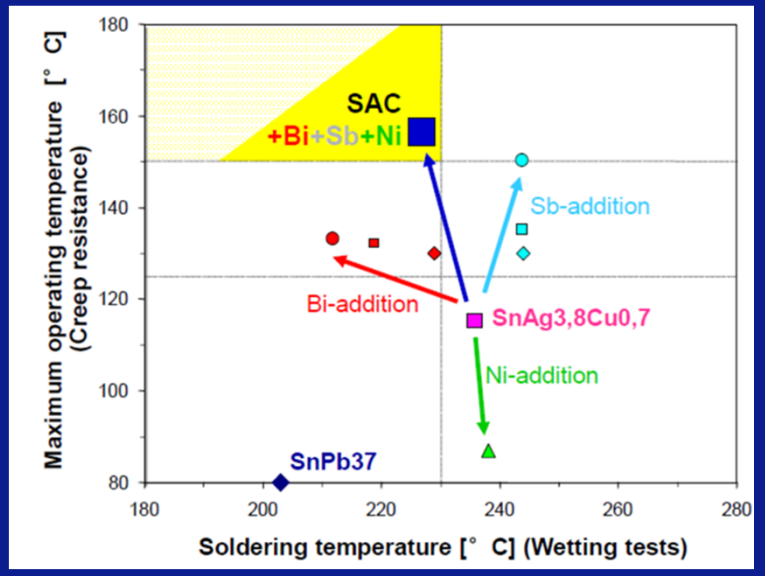
206 to 218°C

Precipitation hardening



Solution hardening





Source:Forrest Lin, Henkel Presentation

Trade names and nominal composition (wt%) of high reliability solder alloys								
Alloy	Developer	Sn	Ag	Cu	Bi	Sb	In	Other
405Y	Inventec	95.5	4.0	0.5				0.05 Ni; Zn
Cyclomax (SAC-Q)	Accurus	92.8	3.4	0.5	3.3			
Ecalloy	Accurus	97.3		0.7	2.0			0.05 Ni
HT1	Heraeus	95.0	2.5	0.5			2.0	Nd
Indalloy 272	Indium	90.0	3.8	1.2	1.5	3.5		
Indalloy 277	Indium	S9.0	3.8	0.7	0.5	3.5	2.5	
Indalloy 279	Indium	89.3	3.8	0.9		5.5	0.5	
Innolot	Heraeus	91.3	3.8	0.7	3.0	1.5		0.12 Ni
LF-C2	Nihon	92.5	3.5	1.0	3.0			
M794	Senju	89.7	3.4	0.7	3.2	3.0		Ni
M758	Senju	93.2	3.0	0.8	3.0			Ni
MaxRel plus	Alpha	91.9	4.0	0.6	3.5			
PS48BR[3]	Harima	Bal.	3.2	0.5	4.0	3.5		Ni, Co
REL22[3]	AIM	Bal.	3.0	0.7	3.0	0.6		0.05Ni; other
REL61[3]	AIM	Bal.	0.6	0.7	2.0			
SB6NX	Koki	89.2	3.5	0.8	0.5		6.0	
SN100CV	Nihon	97.8		0.7	1.5			0.05Ni
SN100CW1	Nihon	95.8		0.7	1.5	2.0		
Violet	Indium	91.25	2.25	0.5	6.0			
Viromet 347	Asahi	88.4	4.1	0.5			7.0	
Viromet 349	Asahi	91.4	4.1	0.5			4.0	

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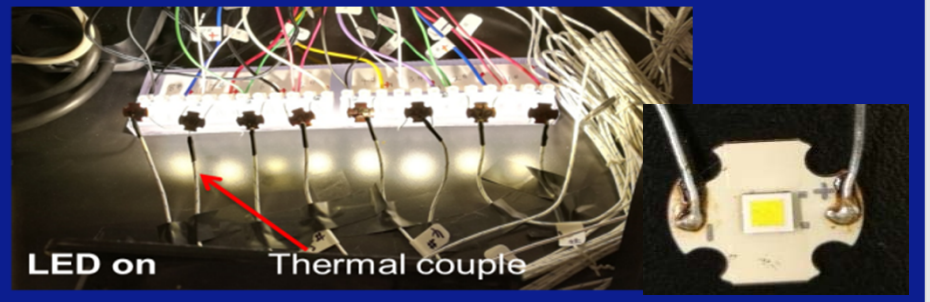
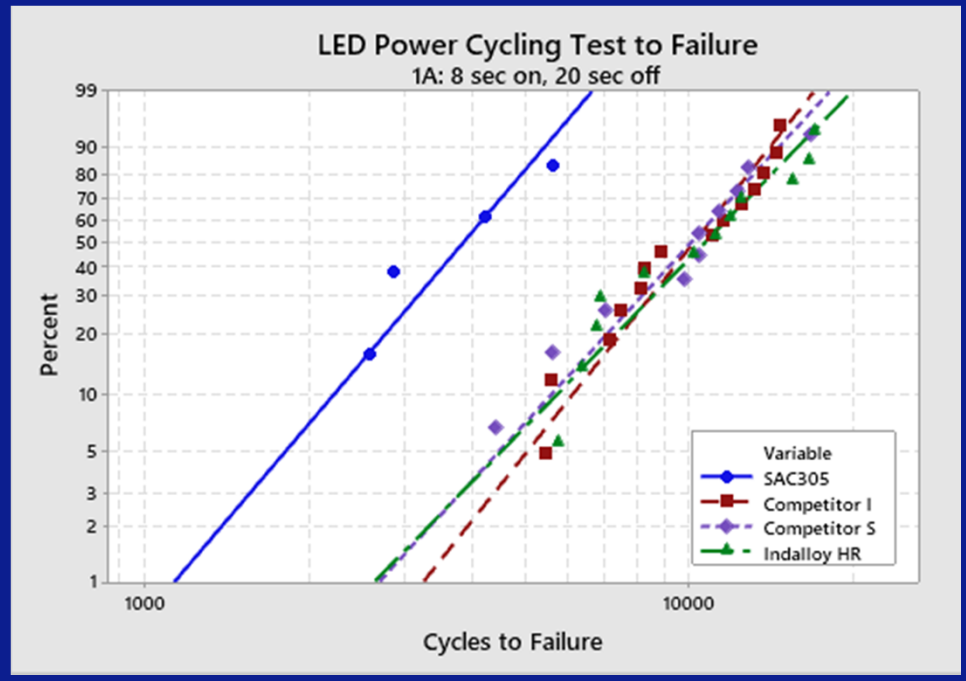
Reliability of 3rd Generation Lead-Free Solders
LED Power Cycling Test

LED power cycling used as an accelerated screening test before committing to thermal cycling



- **Constant current at 1A**
  - Current density 60.6 A/cm^2
- **LED on/off cycle**
  - On 8 sec, then off 20 sec
- **Air cooling fan constantly blowing**
- **Cu board temperature monitoring**
  - Thermal couple attached to back



Reliability of 3rd Generation Lead-Free Solders Thermal Cycling Conditions BGA Components

The performance of high-reliability solders may vary with **package design and testing conditions**

HiRel > SAC305

Same alloy for both bump and paste

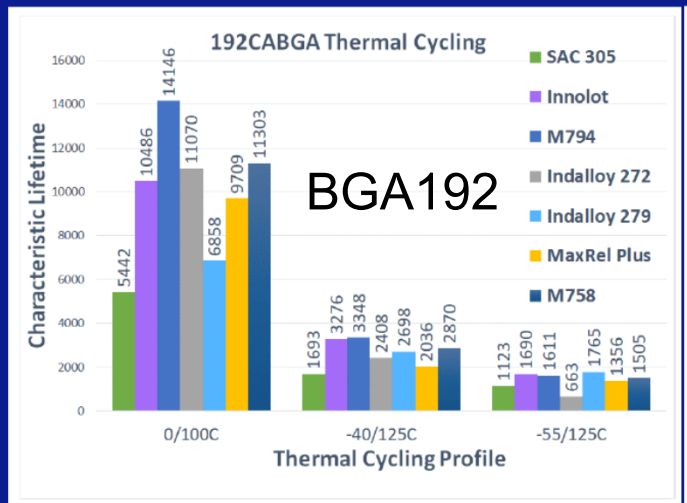


Figure 6. Bar charts comparing the characteristic lifetimes (N63) for the 192CABGA with SAC305 and the 5 high reliability solder alloys tested using 0/100 °C, -40/125 °C and -55/125 °C thermal cycling profiles.

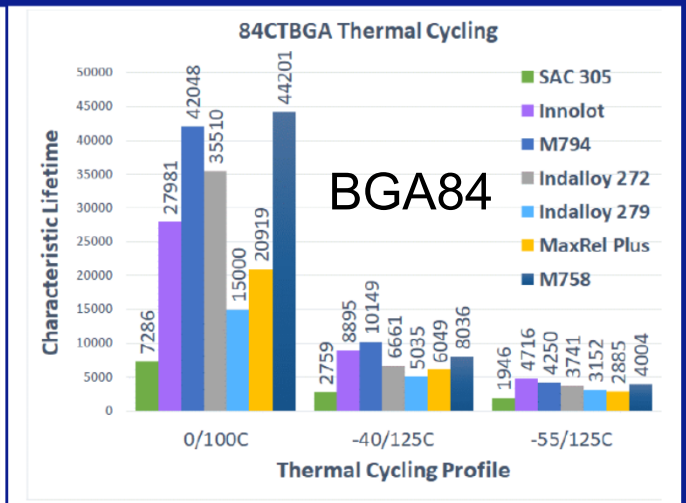


Figure 7. Bar charts comparing the characteristic lifetimes (N63) for the 84CTBGA with SAC305 and the 5 high reliability solder alloys tested using 0/100 °C, -40/125 °C and -55/125 °C thermal cycling profiles.

Source: Ch 7: Lead-free solders for high reliability and high performance applications, by Richard Coyle, in Lead-free Soldering Process Development and Reliability, Edited by Jasbir Bath, Wiley 2020. Richard Coyle etc., Proceeding of SMTAi 2017, 2018, 2019 & 2020

TestConX™

- "Knives that would not cut"
- 7,000 year history of solder
- Solder in the 21st century
- **Sintering innovations**
- Metallic powder system innovations
- Solid metal preform innovations
- Liquid metal innovations
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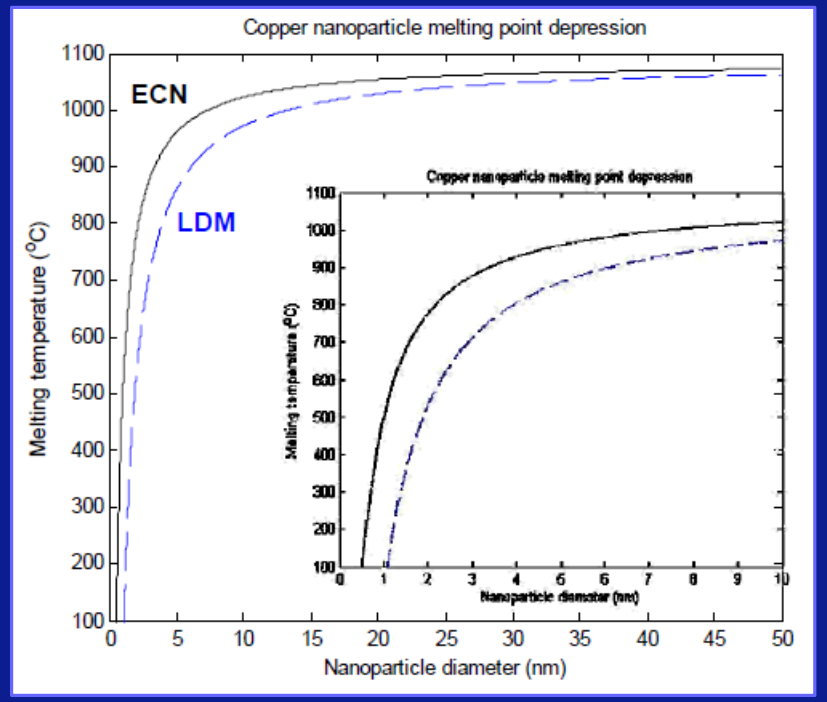
- Hedgehogs and foxes

Nanoparticles and Sintering

- At <<m.p., interdiffusion of surface atoms on adjacent nanoparticles “neck” together, and create an open network of tiny microvoids
- Temperature, pressure, time, and sintering atmosphere are major control variables for sinter joint consolidation



Sources: IPC-4922 (draft) Sintering Materials… Standard
Zinn, “Solder-Free Electronic Assembly Material” SEMATEC 2009

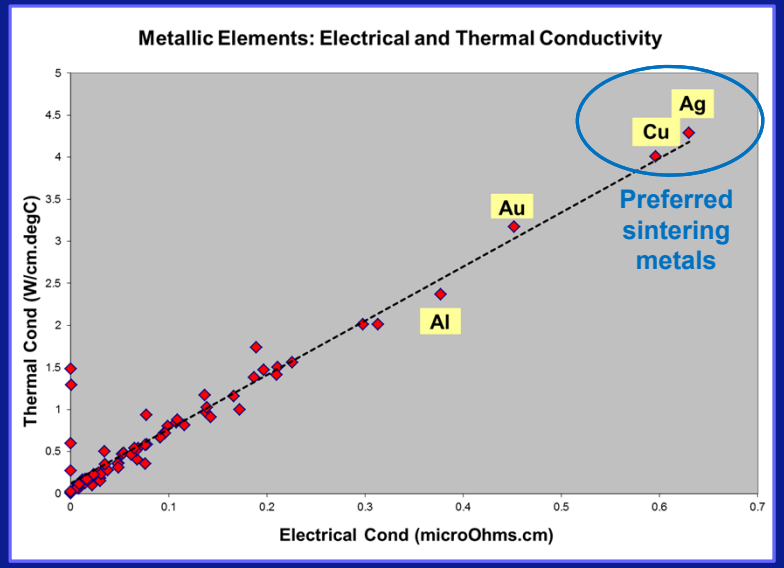
Silver Sintering: Overview

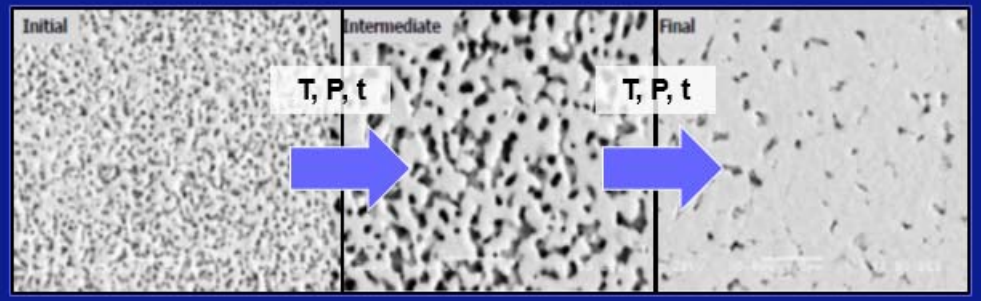
Benefits of silver sintering:

+ High reliability
+ Highest electrical conductivity
+ Highest thermal conductivity
+ High-temperature applications
+ Less reactive than Cu

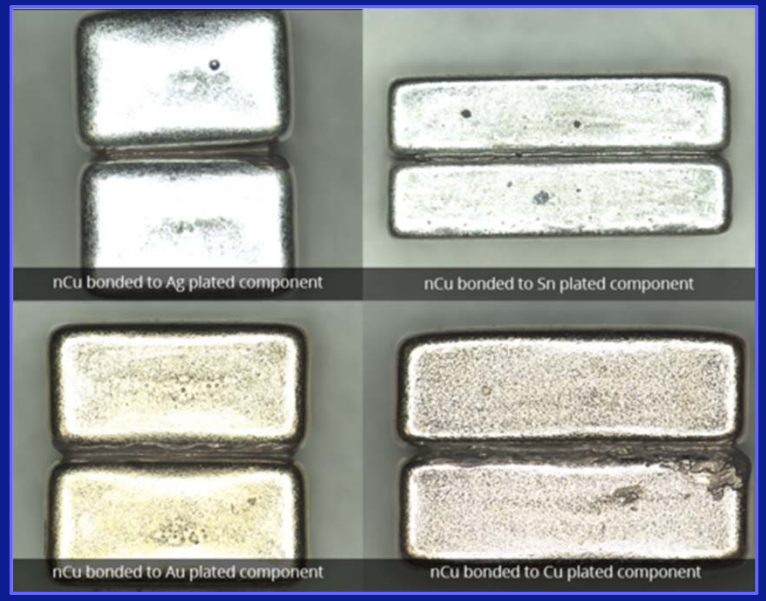
Negative:

- Cost of silver
- Electrochemical migration
- Tarnishing (LEDs)

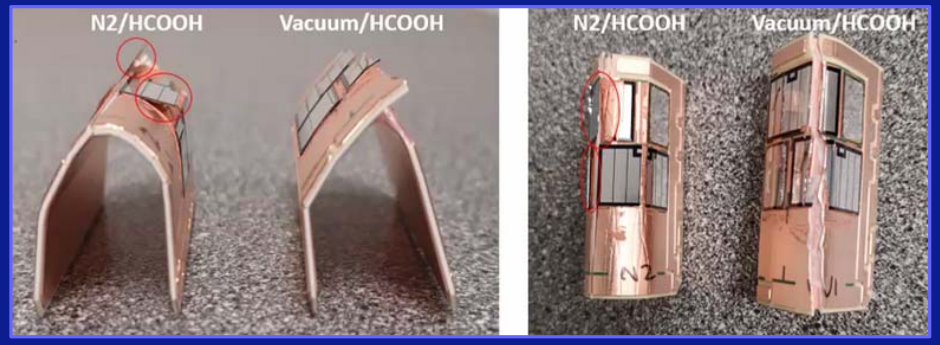




Copper Sintering



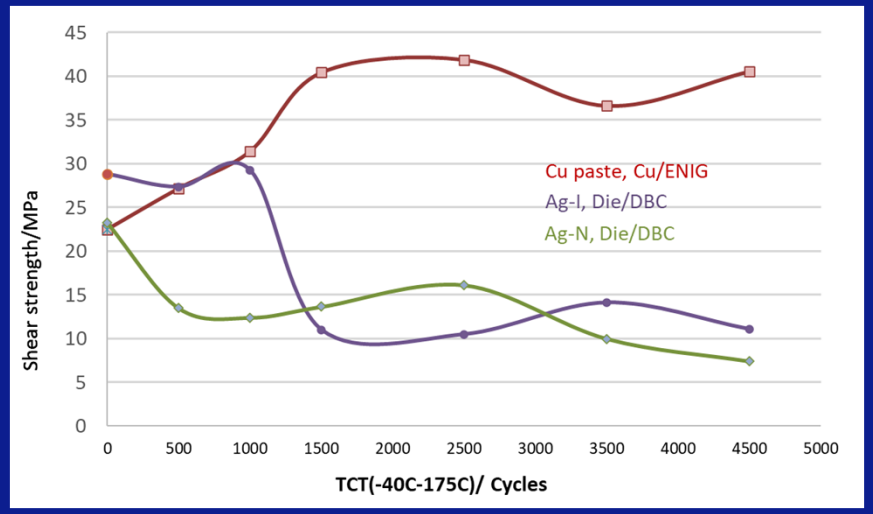
Source: Die Attach — Kuprion Engineered Copper (kuprioninc.com)



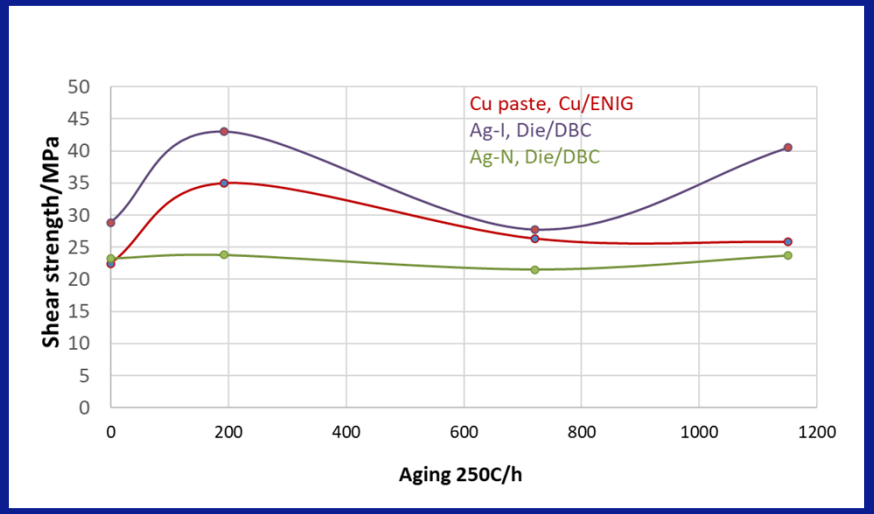
Nanocopper sintering with and without pressure

Cu-Sintering Promising Results

Thermal Cycling



Aging



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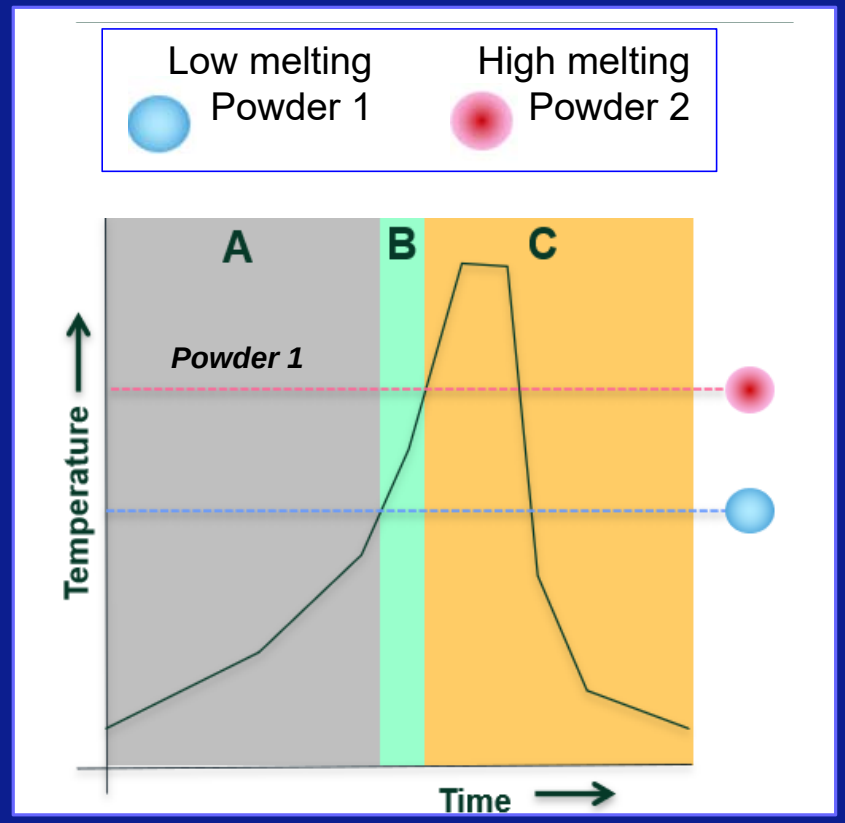
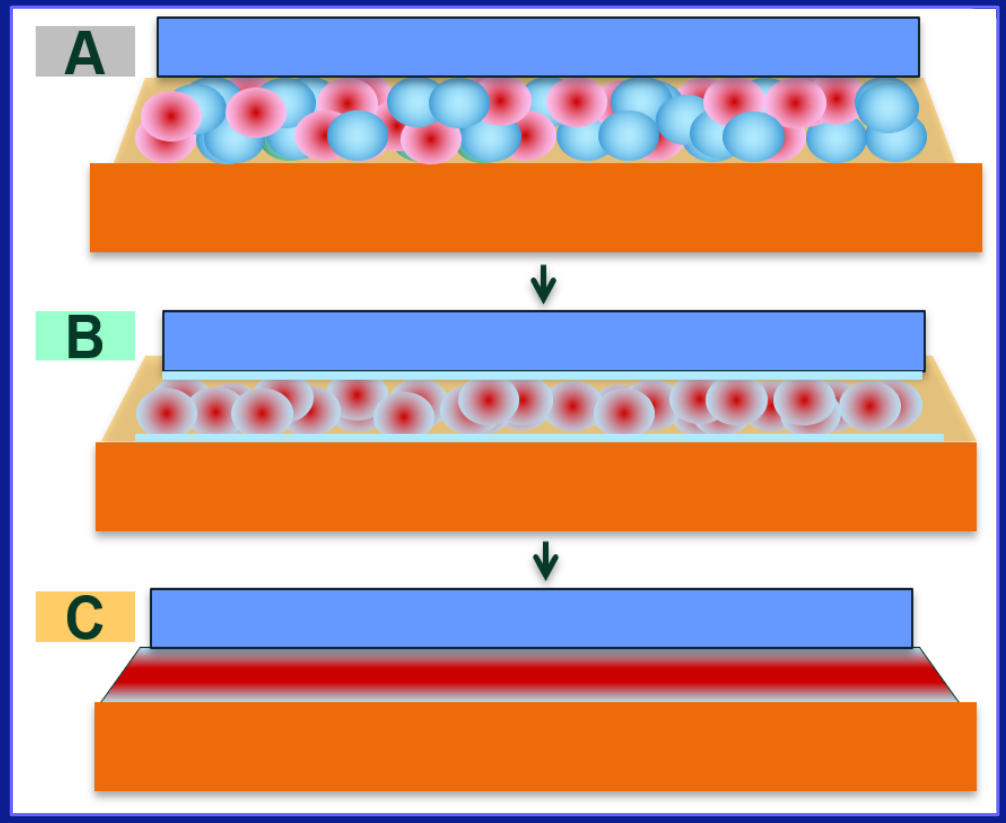
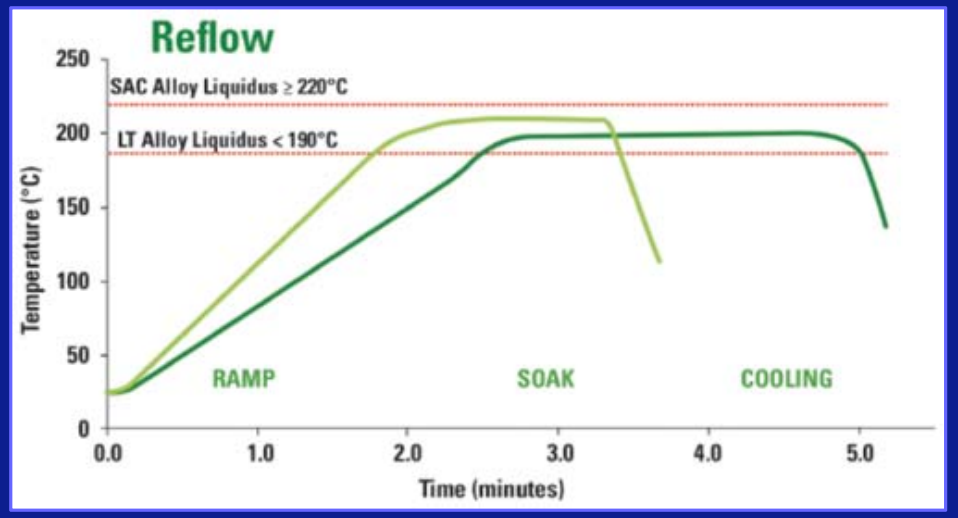
Basis of Mixed-Solder Systems





Solder paste as primary example

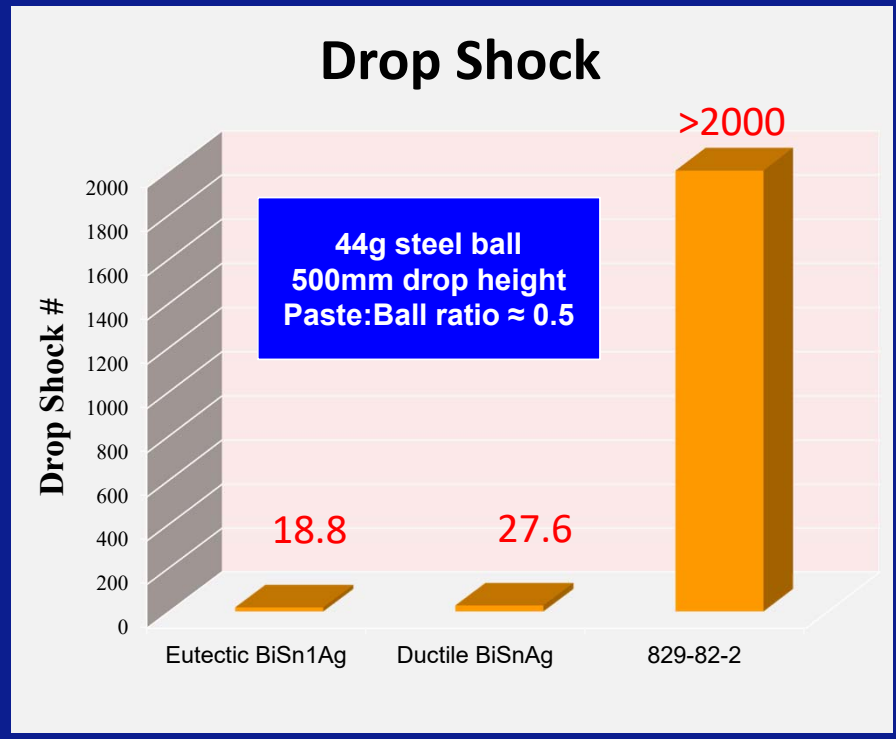
Low/Mid-Temperature Mixed-Powder Technology



L(low)TLF design

- Powder 1: Bi-rich
- Powder 2: Sn-rich

*LTLF = low temperature lead-free



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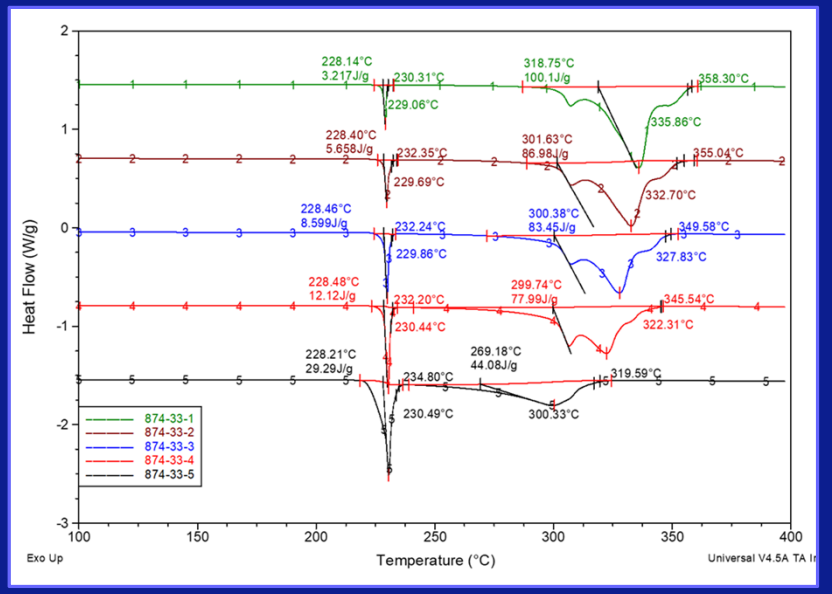
High-Temperature Mixed-Powder Technology

- Trace of Sn-rich low-melting phase remaining after reflow does not reduce the shear strength below 15MPa up to 280°C
- DSC shows effect ratio of Powder 1 (low melting) to Powder 2 (high melting)



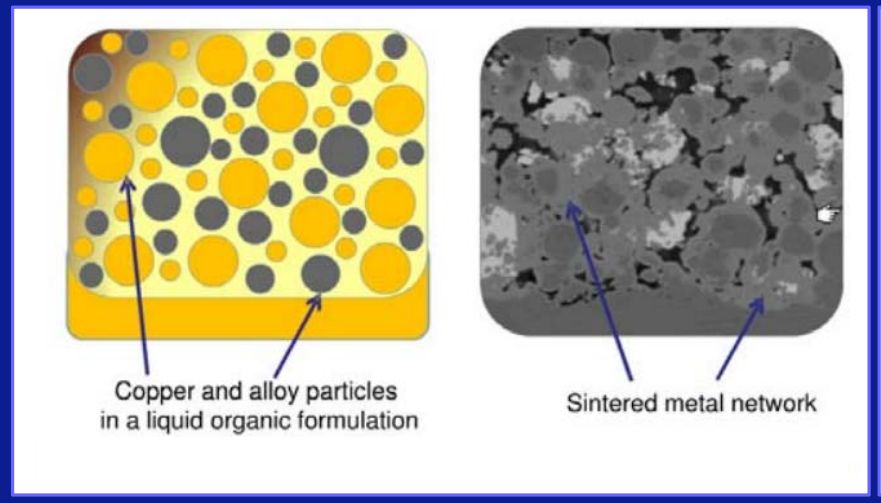
HTLF* design

- Powder 1: Sn-rich
- Powder 2: SnSbCuAg

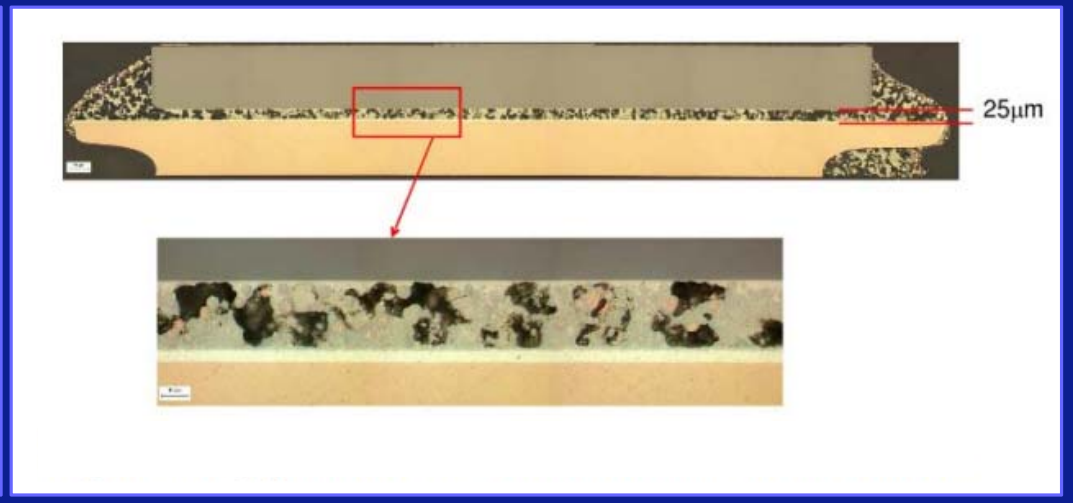
*HTLF = high temperature lead-free

- Ductile Sn-rich phases disperse into the SnSb matrix
- Thermal conductivity (k) ~34W/m.K

Transient Liquid Phase Sintering



Basis of Technology
(Behaves like a Solder Paste)



TLPS Paste for Die Attach

Source: Neuhaus, ALTERNATIVES TO SOLDER IN INTERCONNECT, PACKAGING, AND ASSEMBLY

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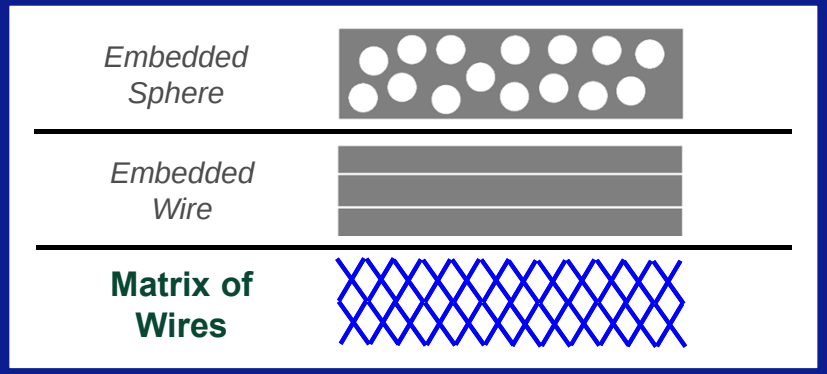
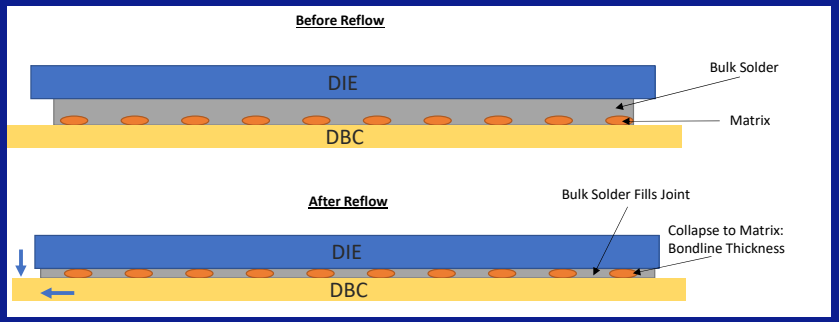
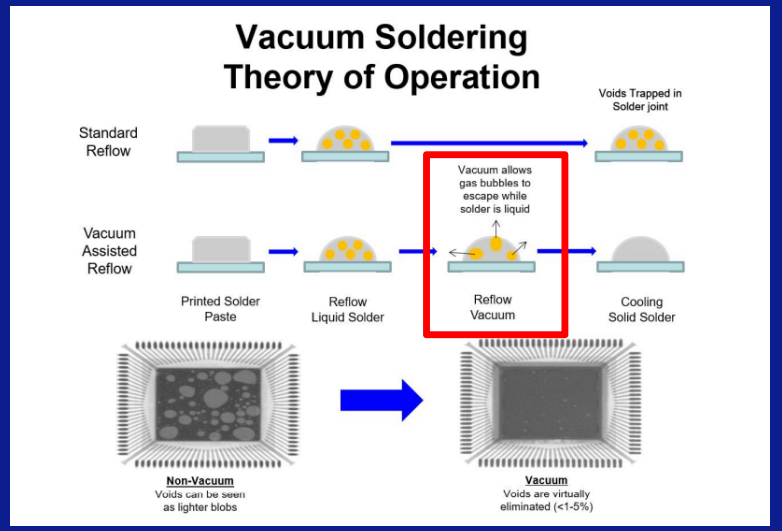
Metal Preforms: Composite Solders for Bondline Control

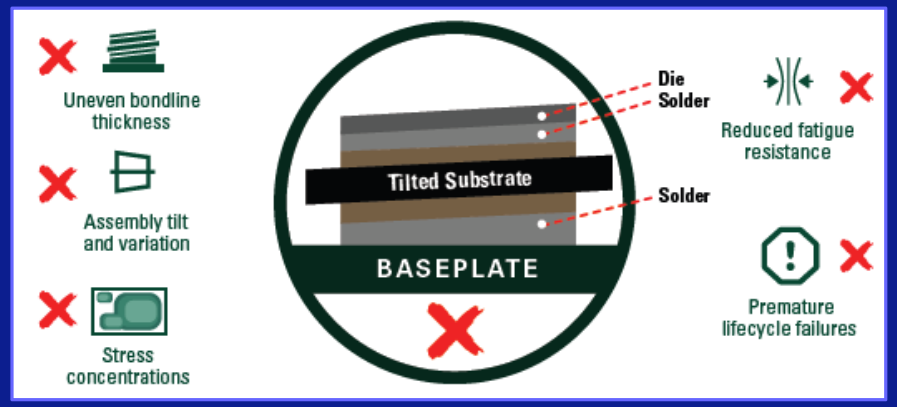






Metal Preforms: Composite Solders for Bondline Control

The Challenge: Bondline Thickness (BLT) Control



Uneven stress distribution

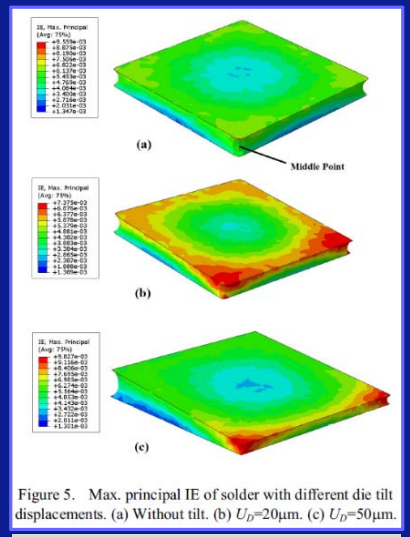
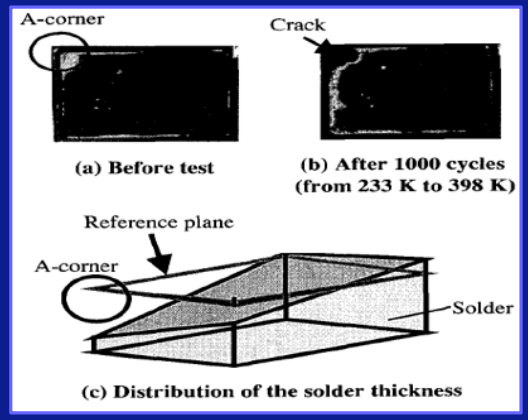


Figure 5. Max. principal IE of solder with different die tilt displacements. (a) Without tilt. (b) U_D=20μm. (c) U_D=50μm.

*K. Hayashi & G Izuta, "Improvement of Fatigue Life of Solder Joints by Thickness Control of Solder with Wire Bump Technique", ECTC 2012.

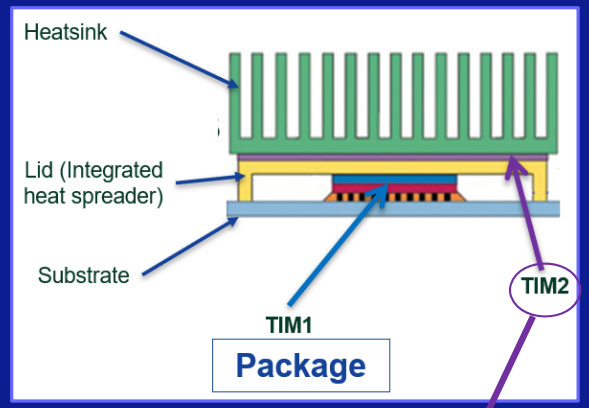
Tilt leads to crack propagation

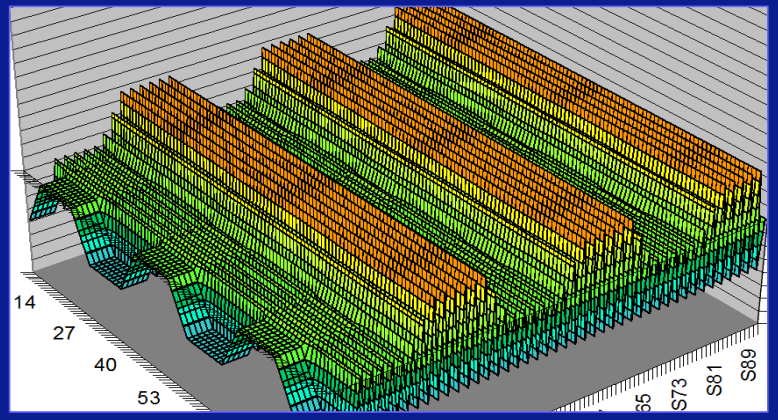


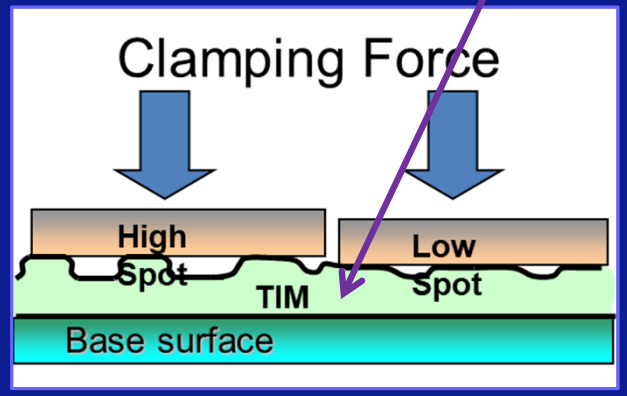
TestConX™

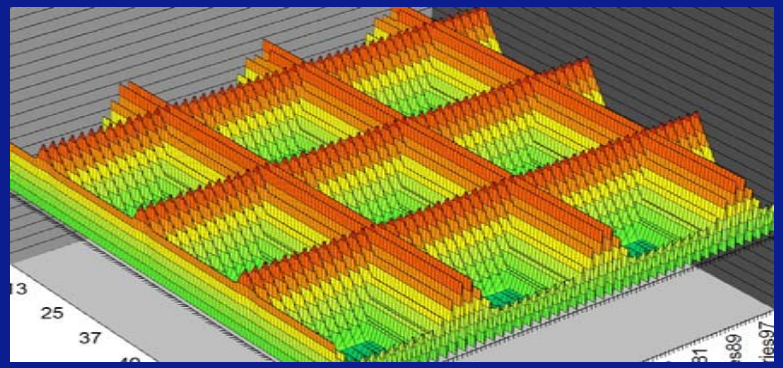
Fulcrum of Innovation: From Chemistry to Metallurgy

Metal Preforms: Compressible Metal TIM 2



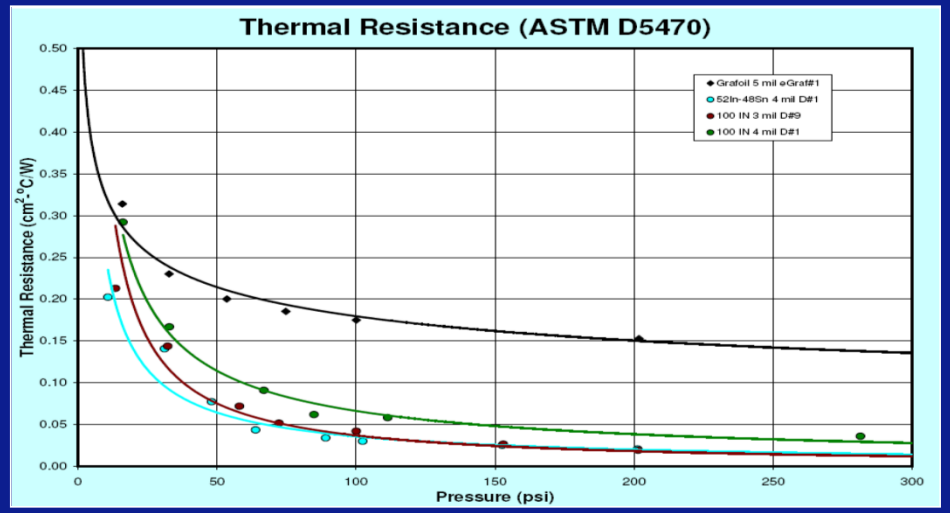




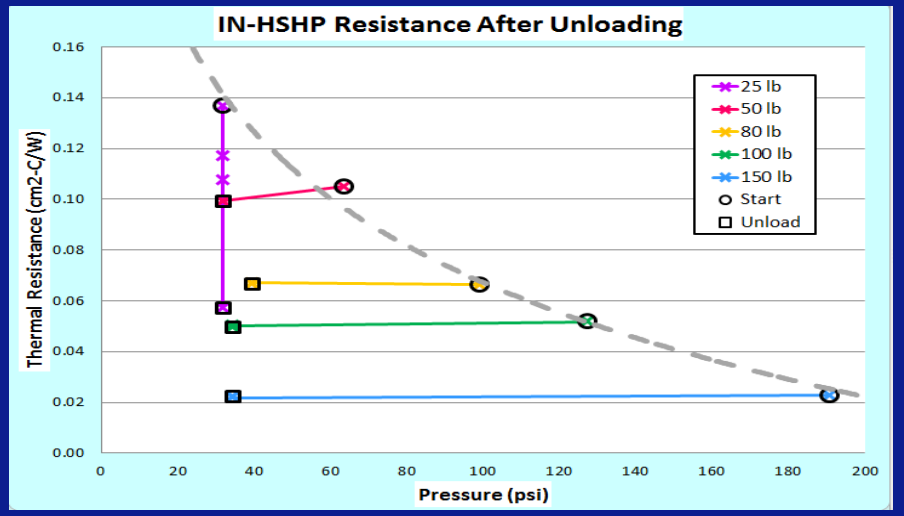


Source:
US Patent 7,593,228-B2

Metal Preforms: Compression Force



Graphite foil has low thermal conductivity in Z-axis due to its structure



Relaxing the compressive force does not degrade the thermal conductivty

TestConX™

Fulcrum of Innovation: From Chemistry to Metallurgy

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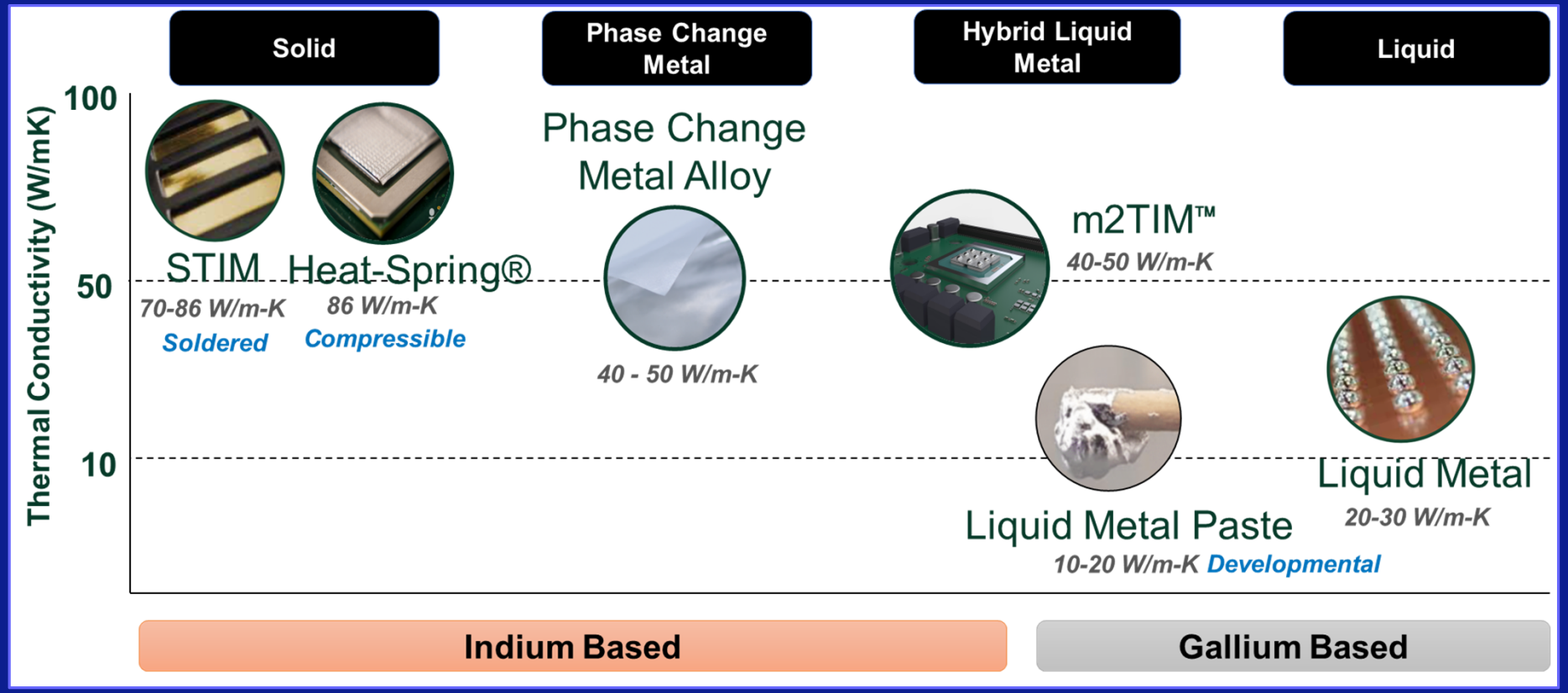
2022

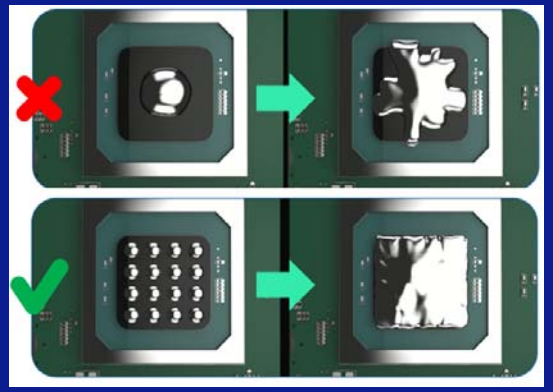
- "Knives that would not cut"
- 7,000 year history of solder
- Solder in the 21st century
- Sintering innovations
- Metallic powder system innovations
- Solid metal preform innovations
- **Liquid metal innovations**
- Major drivers of innovation
- Hedgehogs and foxes

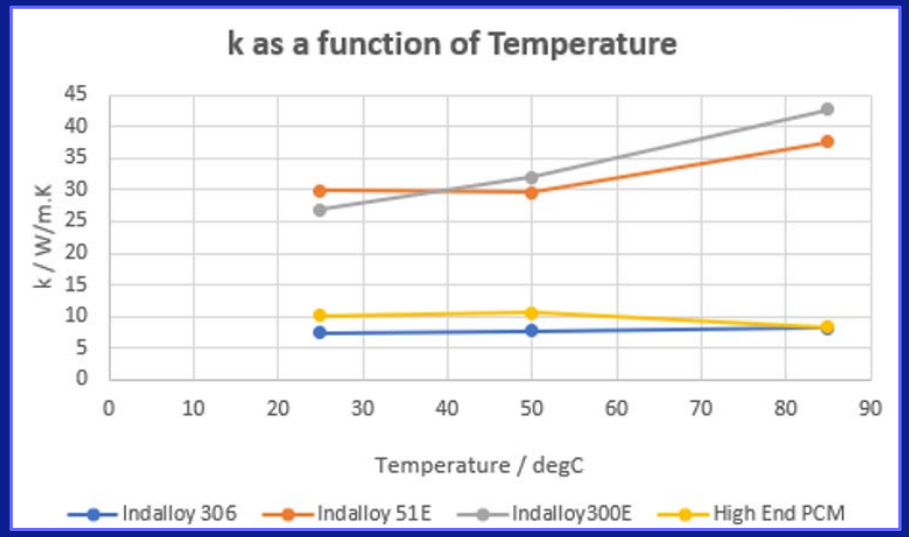
Indium and Gallium – Core to New Technologies



Liquid Metal Overview

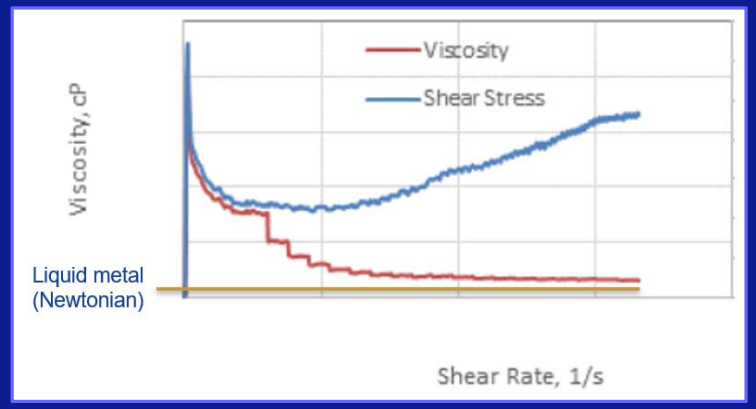
- Attributes
  - Ultralow BLT
  - High thermal conductivity
  - Excellent wetting to surfaces
  - No soldering or surface metallization needed
  - Thin bondline possible
- Minor Challenges
  - Incompatible with some metals
  - Implementing automation
- Major Challenges
  - Must be contained to minimize spread (electrically conductive)
  - Oxidation
  - Pump Out





Liquid Metal Paste (LMP) Technology

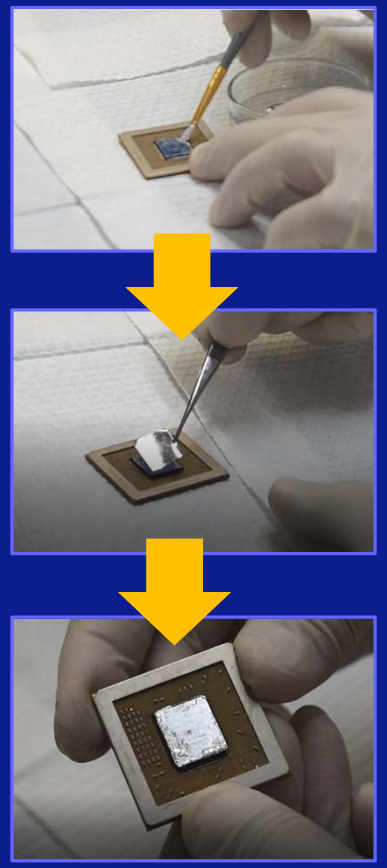
- Rheology control for:
  - Deposition method
  - Anti-leaking properties
  - Thermal resistance
  - Bondline thickness
  - Reliability

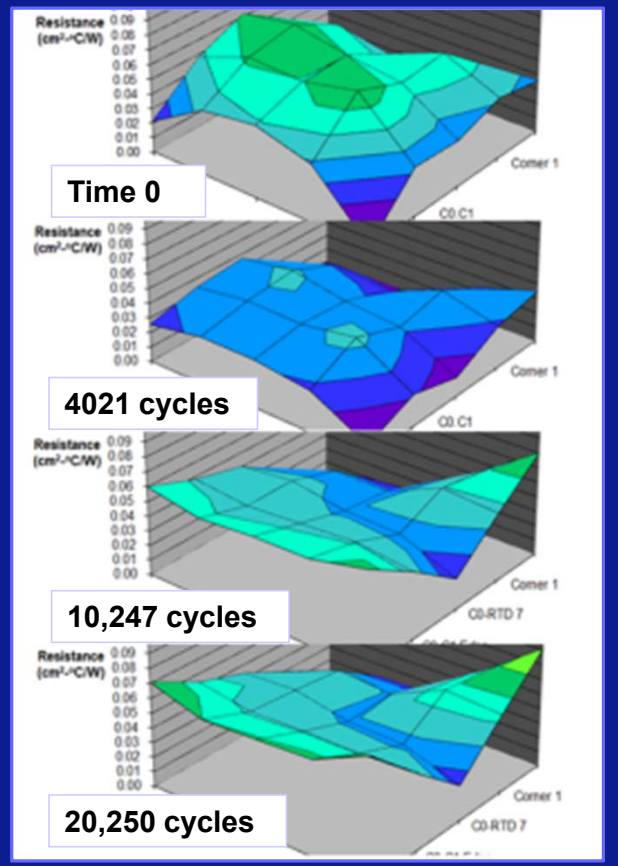


TestConX™

HLM Created During Chip Assembly: m2TIM™

- Apply liquid metal via dispensing or jetting
- Place a solid solder preform onto the liquid metal
- Solid alloy must be highly soluble in Ga
- Ga diffuses through solid metal to make a hybrid liquid metal (HLM)



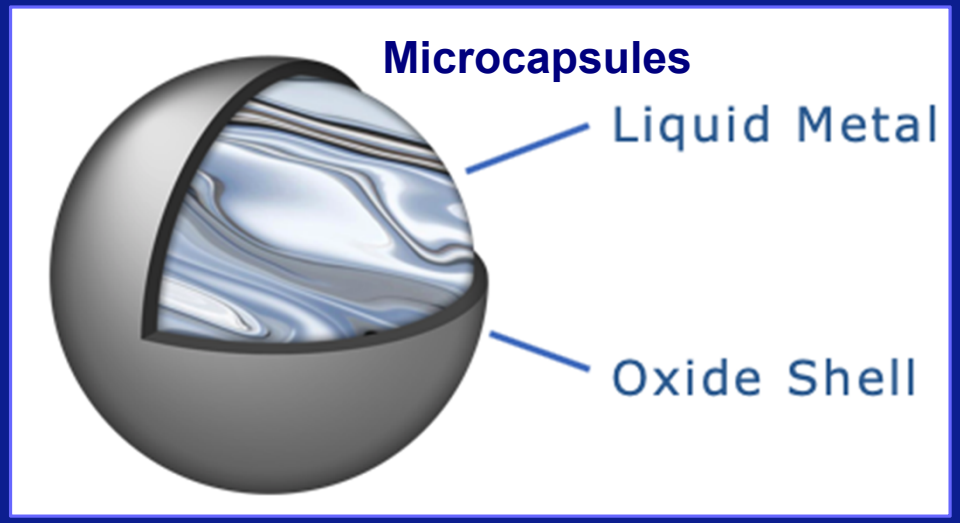


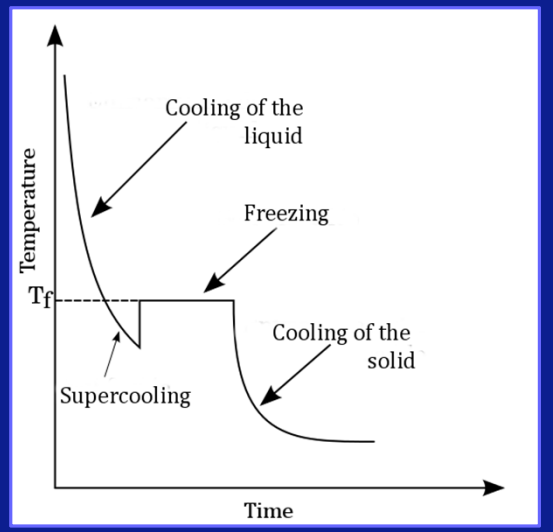
- Die was power cycled over 20,000 times with no degradation
- TjMAX ~105°C.

TestConX™

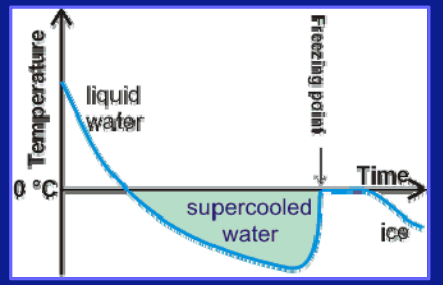
Fulcrum of Innovation: From Chemistry to Metallurgy

Emergent Supercooled Powders





SAC305 Supercooled Soldering 180°C BGA Attach



Source: Safi-Tech

- "Knives that would not cut"
- 7,000 year history of solder
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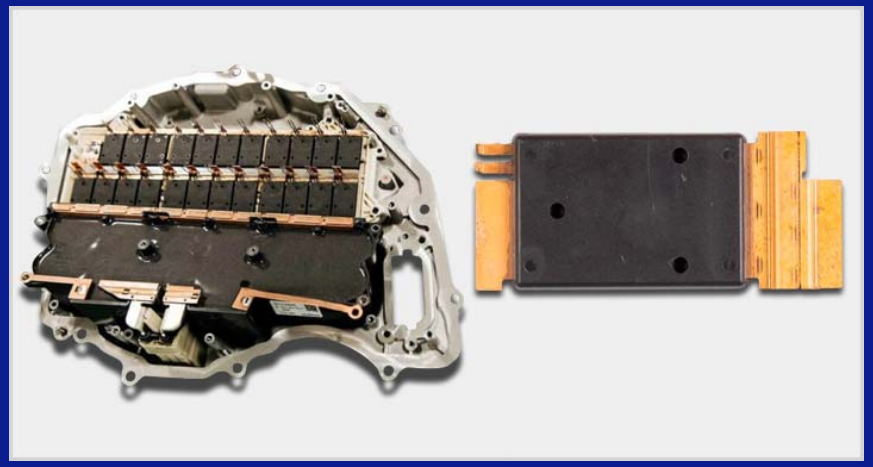
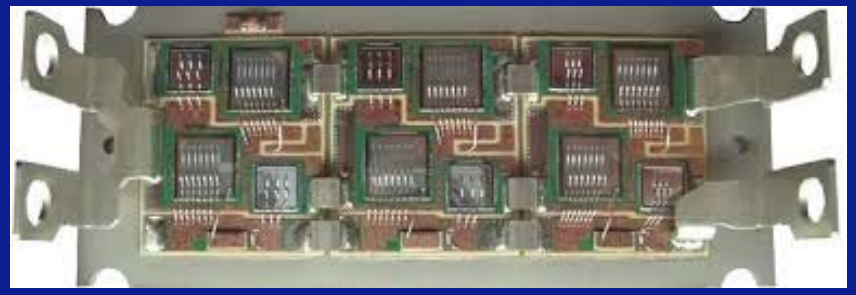
- Metallic powder system innovations
- Solid metal preform innovations
- Liquid metal innovations
- **Major drivers of innovation**
- Hedgehogs and foxes

Automotive: Electric Vehicle Drive Train

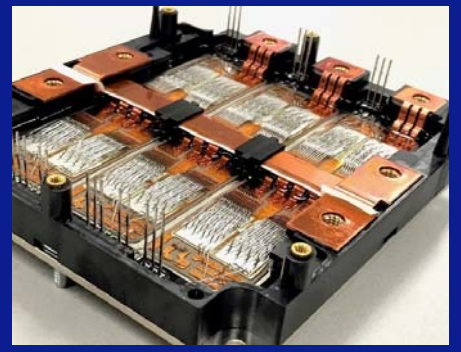
Tesla Model 3 Traction inverter, showing the SiC MOSFET power modules



Source: appliedmaterials.com and PntPower



Source: Semikron

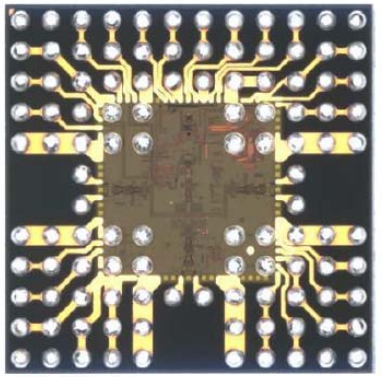


1st Generation Chevy Volt
Source: Weber.edu

CPUs: Previously @ BITS: Package Complexity

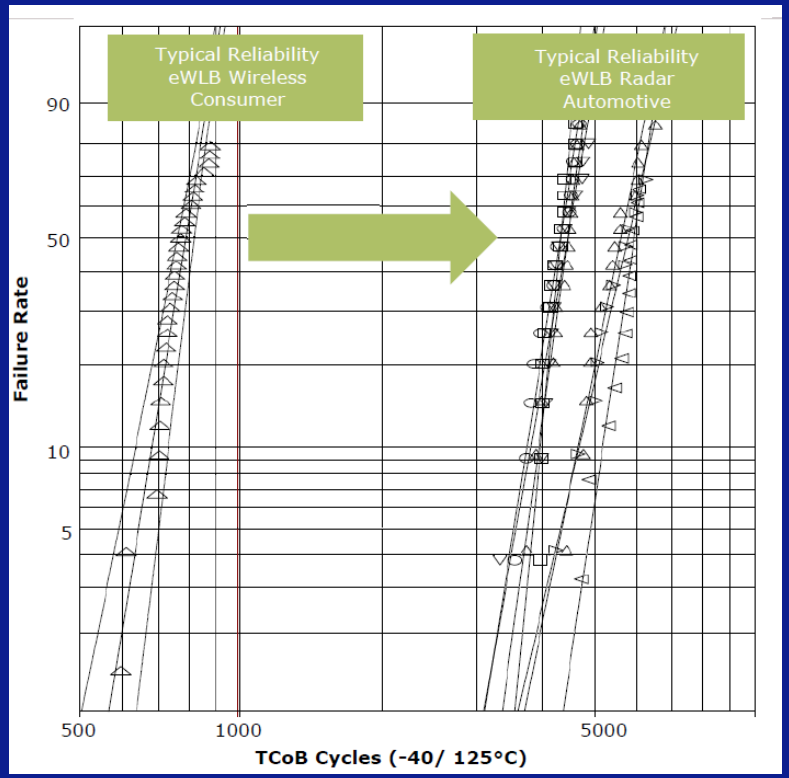
E. Jan Vardaman
TechSearch International

Automotive: Consumer Electronics Meet Automotive Standards



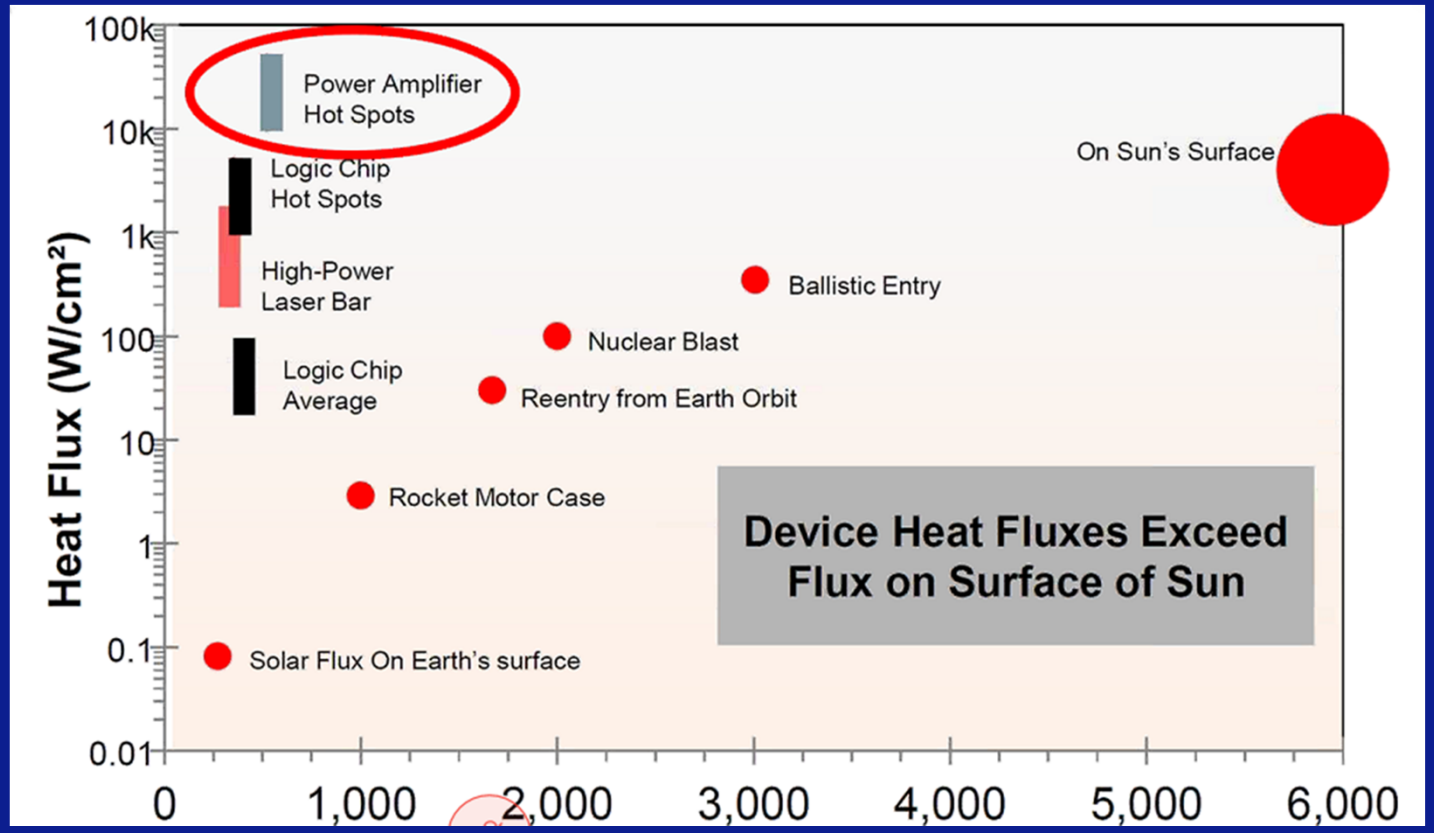
eWLB Radar

eWLB Radar
Cross section on board



Source: Infineon

CPUs: Reaching Thermal Limits



Source: Avram Bar-Cohen, Raytheon

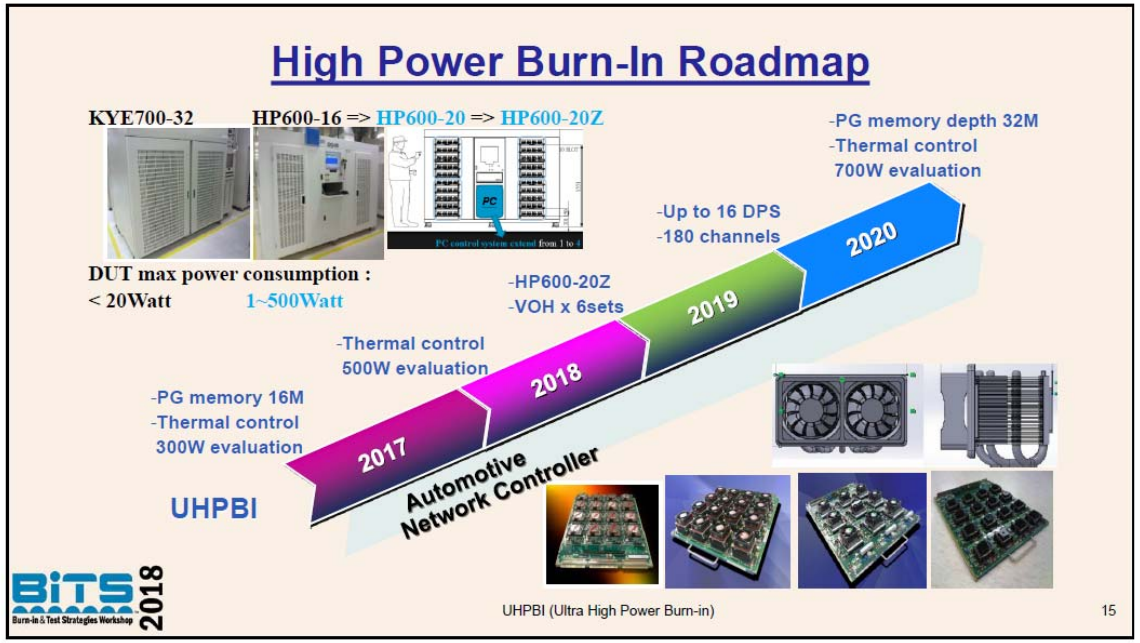
CPUs: Previously @ BITS: Burn-In Roadmap

Joe Lin
KYEC
Jason Wang
KYEC USA

BiTS 2018

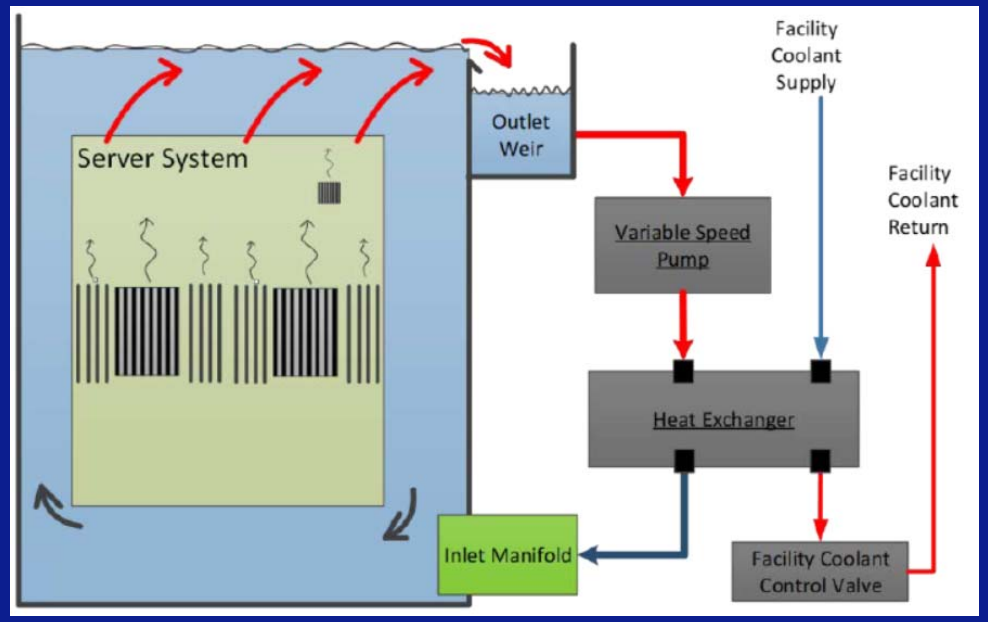
Session 1B Presentation 4

A Better Workhorse
- Burn-in Printed Circuit Boards & Solutions

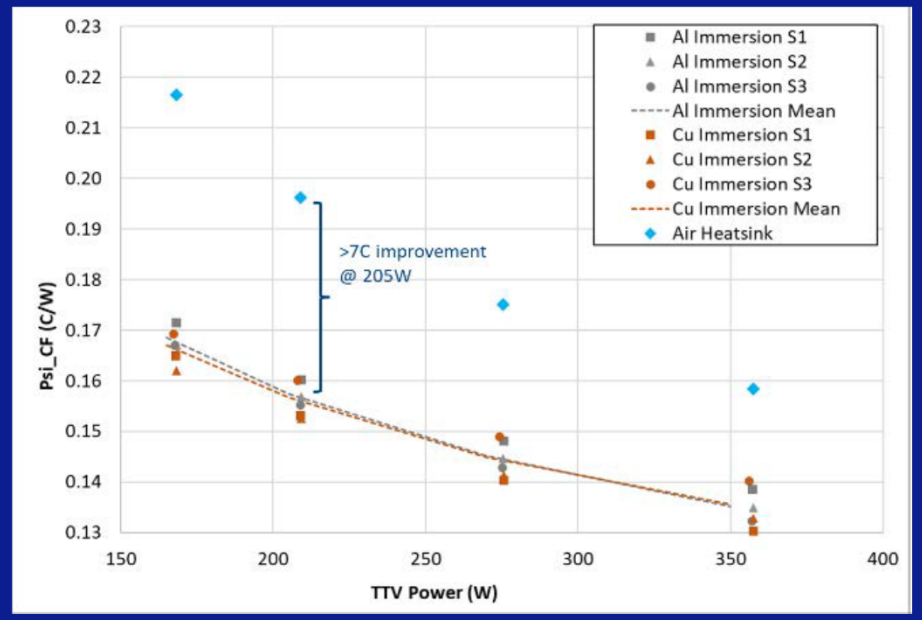


Burn-in & Test Strategies Workshop www.bitsworkshop.org March 4-7, 2018

CPUs: Immersion Cooling



>7°C Improvement



Source: Sarangi, Single-Phase Immersion Cooling

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- **Hedgehogs and foxes**

Need: Focused Frogs and Visionary Birds
Hedgehogs & Foxes

Freeman Dyson

The Greek poet Archilochus wrote, "the **fox** knows many things, but the **hedgehog** knows one big thing."

TestConX™

Device Reliability Evolution Drives Materials Innovation

Key differentiating reliability need

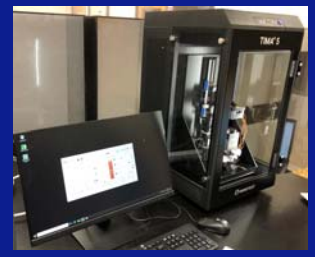
Drop shock

Thermal cycling

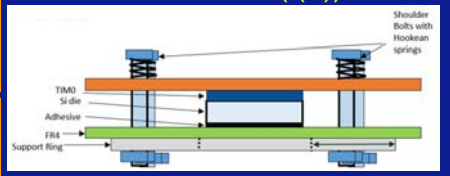
HTOL / Power cycling

Test Method	Comments	Primary TIM Type (1/0)
Bulk thermal conductivity	50C ASTM D-5470 (30, 85C)	ALL
Shelf-life	-40 to +35C typical	ALL
Drop-shock	JESD22-B104C	TIM0, TIM1
Reflow resistance	3, 4 or 5x reflow to 260C	TIM1 (BGA)
Thermal shock	JESD22-A106B	TIM1
Thermal cycling	JESD22-A104E	TIM0, TIM1
HAST	JESD-22-A118	TIM0, TIM1
HTOL	JESD22-A108C	TIM0, TIM1
Power cycling	Up to 1000W/cm2	TIM0
Vibration	JESD22-B103B	TIM0, TIM1

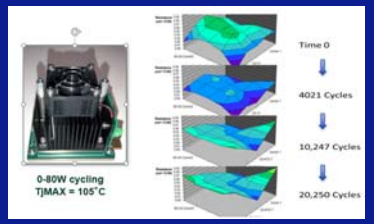
- Reliability testing must evolve to match system-level mission profiles



Bulk K data (f(T))



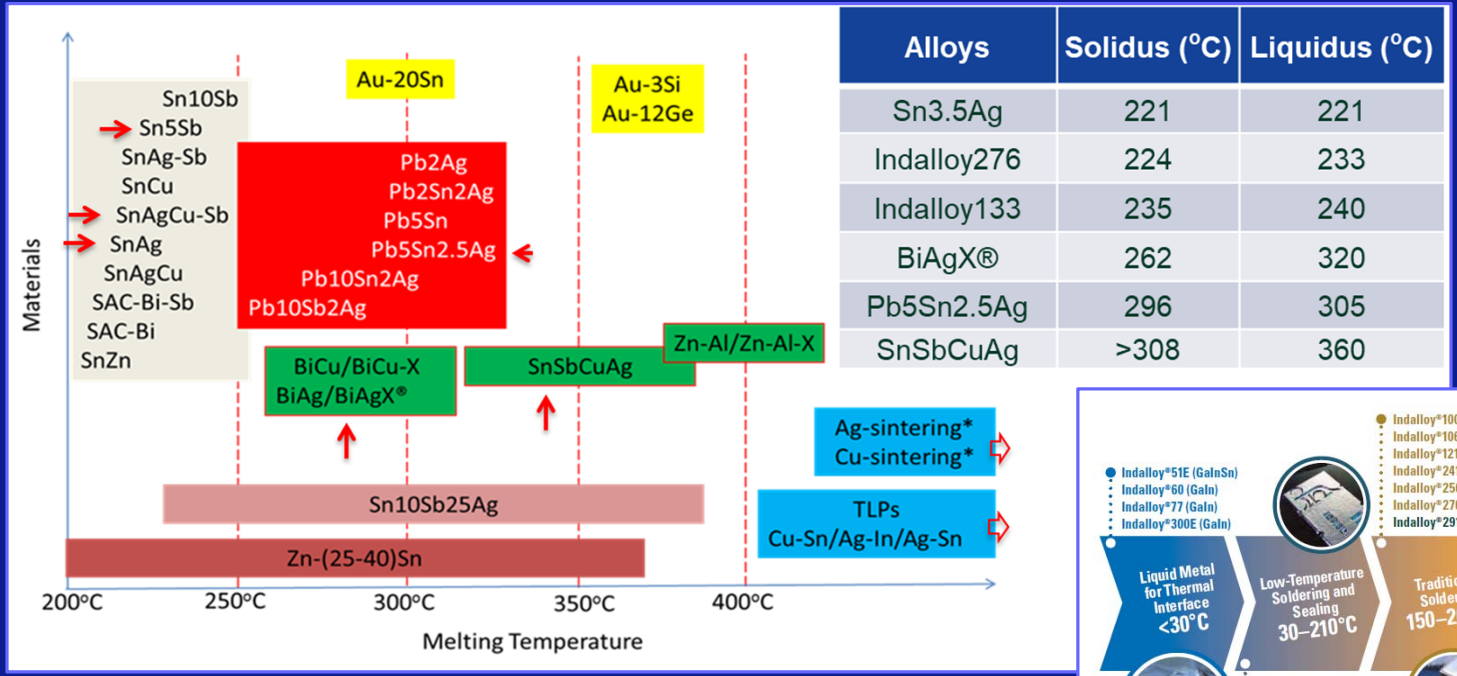
Test vehicle for thermal cycling/shock



Power cycling

TestConX™ 2022

Evolving Solder Alloy Technology



Alloys	Solidus (°C)	Liquidus (°C)
Sn3.5Ag	221	221
Indalloy276	224	233
Indalloy133	235	240
BiAgX®	262	320
Pb5Sn2.5Ag	296	305
SnSbCuAg	>308	360

Our Ingredient List is limited. . .
. . . and the Combinations are Endless

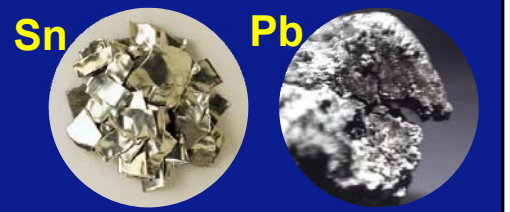
Periodic Table of Solder Elements

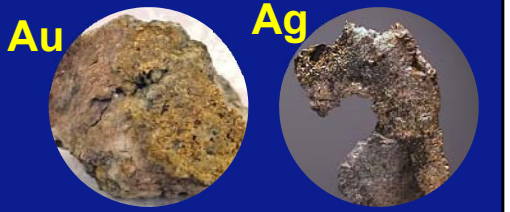
Elemental Group Number																
1	2	IIIa	IIIb	IV	V	VI	VII	VIII	IX	X	XI	XII	3	4	5	6
Li	Be												B	C		
Na	Mg												Al	Si	P	S
K	Ca	Sc		Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se
Rb	Sr	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te
Cs	Ba	La	Ce	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	

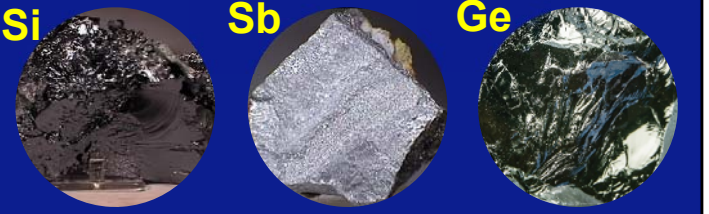
Key		
		Used at % levels in solders
		May be added in small quantities
	Xy	Highly toxic
	Xy	Highly reactive with oxygen/moisture
	Xy	Highly expensive
	Xy	No known use in solder

Omits gaseous and highly radioactive elements

Prepared by: Andy Mackie







TestConX™

Fulcrum of Innovation: From Chemistry to Metallurgy

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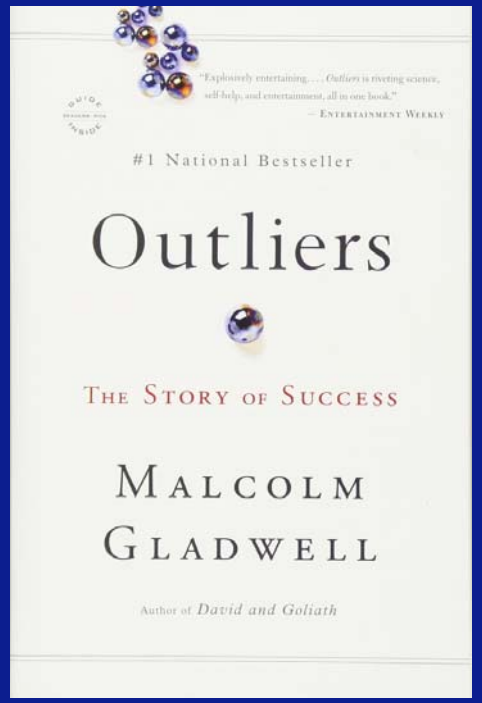
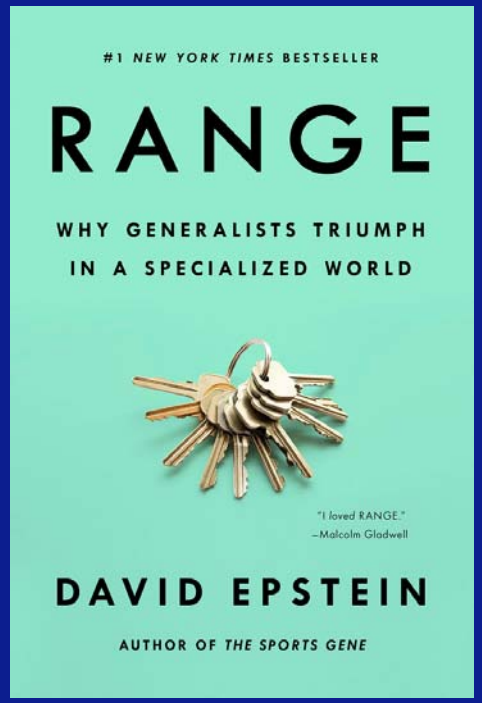
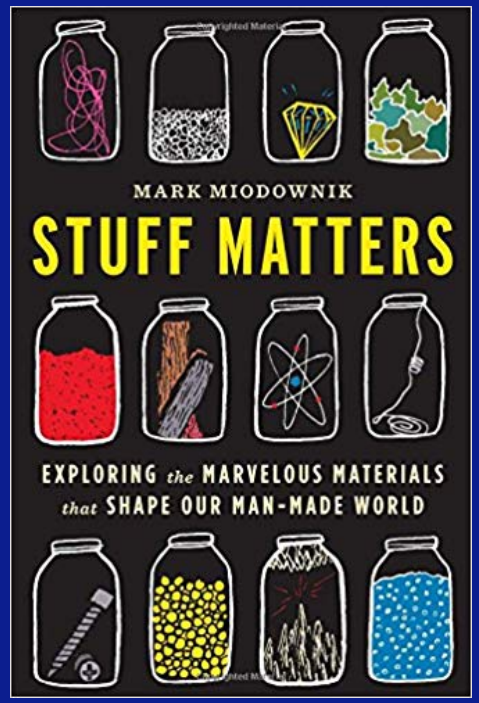
2022

Discussion

Recommended Reading







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