Willkommen
Welcome
Bienvenue

Materials Science & Technology

Recent Developments of Joining Technologies for Ever-more Complex Industrial Requirements

Lars P.H. Jeurgens

Empa, Laboratory for Joining Technologies & Corrosion
Überlandstrasse 129, 8600 Dübendorf, Switzerland

Email: Lars.jeurgens@empa.ch

Workshop “Photonics Packaging for Harsh Environments”, Alpnach, 8 June 2015

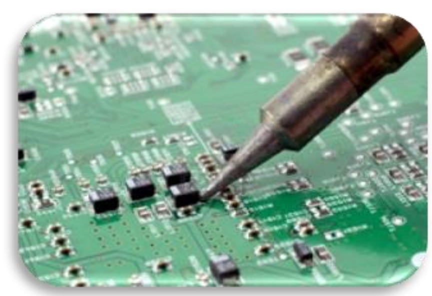
Joining Technologies

Industrial requirements

- ✓ Joining of heat-sensitive materials and miniaturized components.
- ✓ Extended service lifetime of joint assemblies in harsh environments.

Process and service requirements

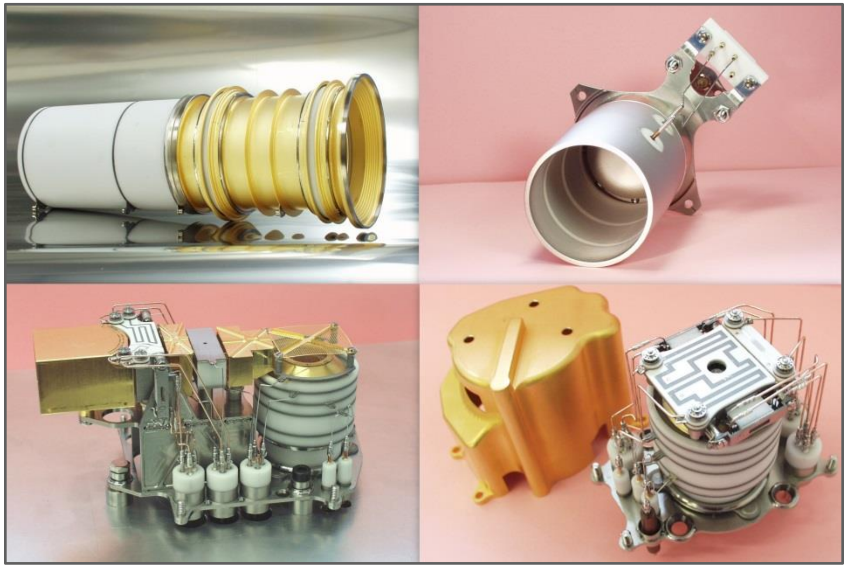
- ✓ Fast joining at ever-lower temperatures
- ✓ Long-term mechanical and chemical stability during operation
  - ➢ at elevated temperatures
  - ➢ under fast cyclic thermo-mechanical loading conditions.
  - ➢ in high shock and vibration environments.
  - ➢ in moisture, ionic liquids and reactive gas atmospheres (under high pressures).



Packaging for harsh environments

Harsh environments for joint assemblies

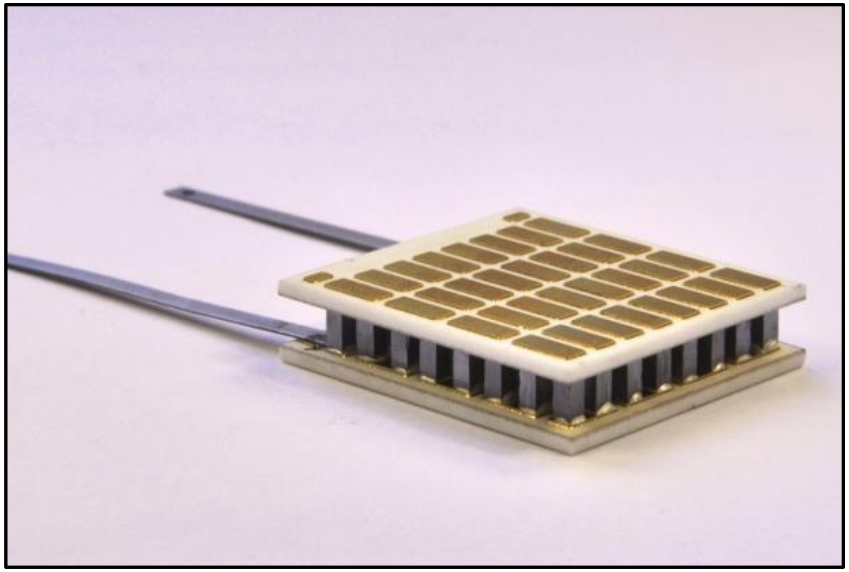
- ✓ Rapid thermal cyclic in the range of -40 °C up to 250 °C.
- ✓ Operation beyond 125 °C in high shock and vibration environments.
- ✓ Operation in moistures and ionic liquids (i.e. high corrosion resistance).
- ✓ Operation in reactive gas atmospheres under high pressures.



Fabricated @ Empa:

Ion-Optical Components for ROSINA RTOF

(University of Bern / ESA mission Rosetta)



TLP-Bonded @ Empa :

Thermoelectric module for exhaust applications

Recent Developments of Joining Technologies for Ever-more Complex Industrial Requirements

@

Laboratory for Joining Technologies & Corrosion

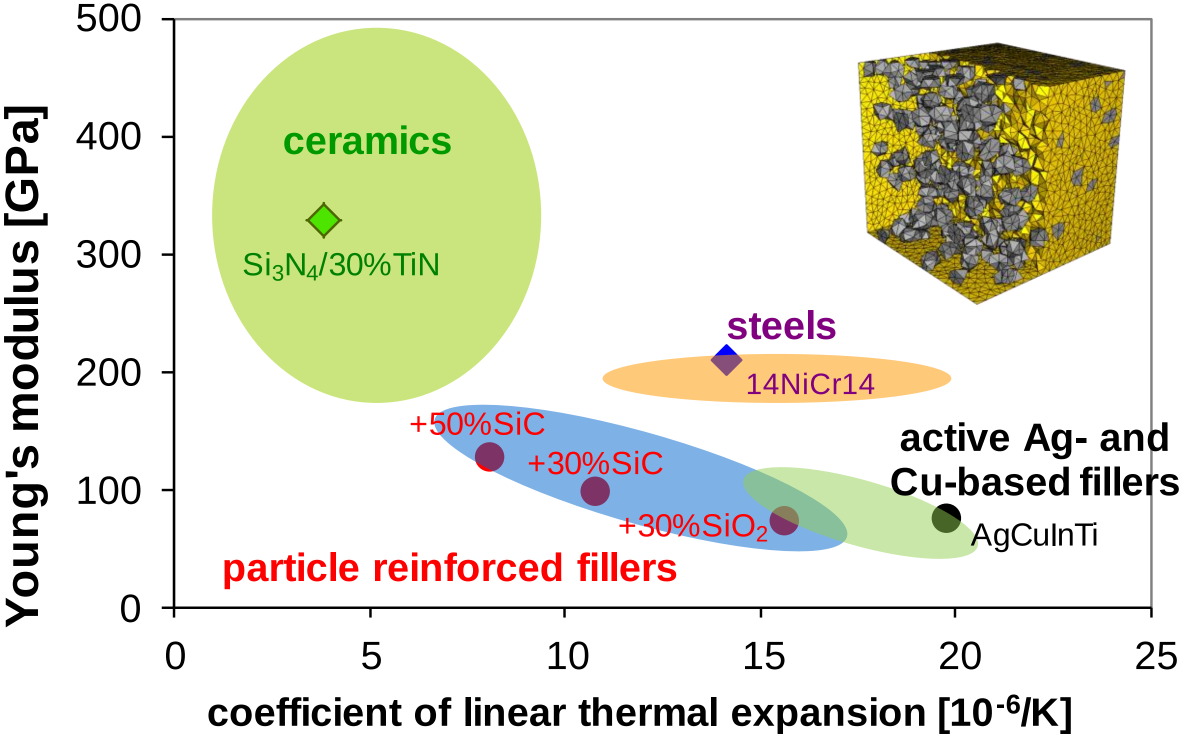
@

EMPA

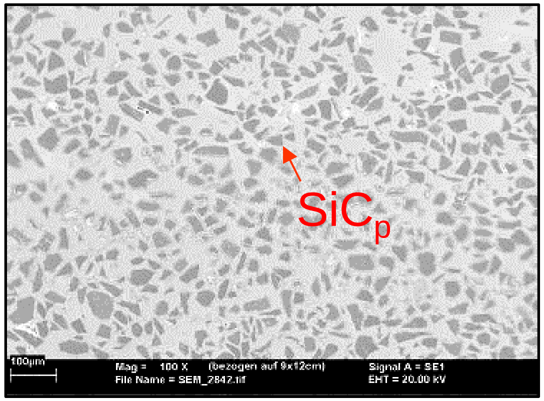
Materials Science & Technology

Application of particle-reinforced brazing fillers for improved mechanical performance

EMPA Materials Science & Technology



AgCuInTi/glass (d=60µm)



CuSnTiZr/SiC_p (d=25µm)

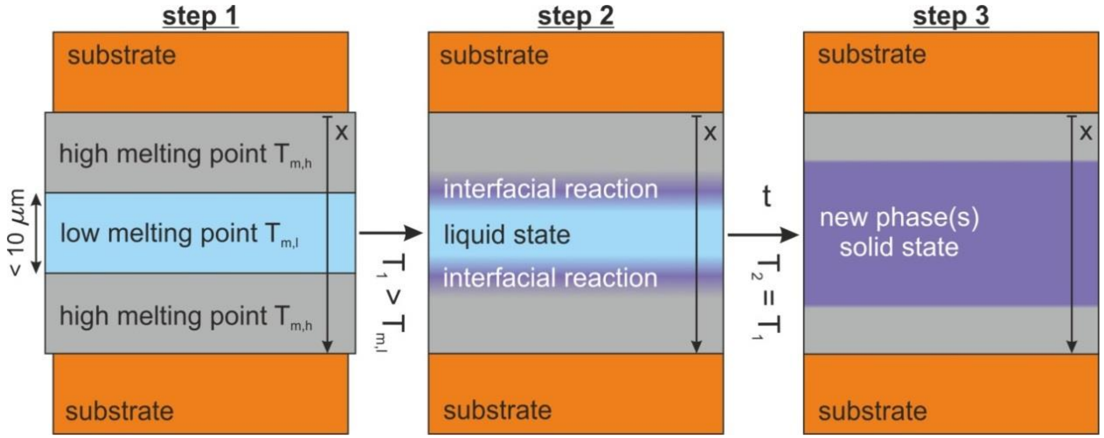
Particle reinforced brazing fillers provide tuneable physical properties, which can be tailored to reduce thermomechanical stresses of joint assemblies during operation.

Transient Liquid Phase (TLP) Bonding

EMPA Materials Science & Technology

Advantages of the TLP process

- Fast joining < 250 ºC
- Operation >> 250 ºC



Basic Principles of the TLP process

Common TLP systems

Low-melting-point metal

- Sn ($T_{m,l}$ = 232 ºC)
- In ($T_{m,l}$ = 157 ºC)

+

High-melting-point metal

Ag, Cu, Ni or Au

Process optimization issues

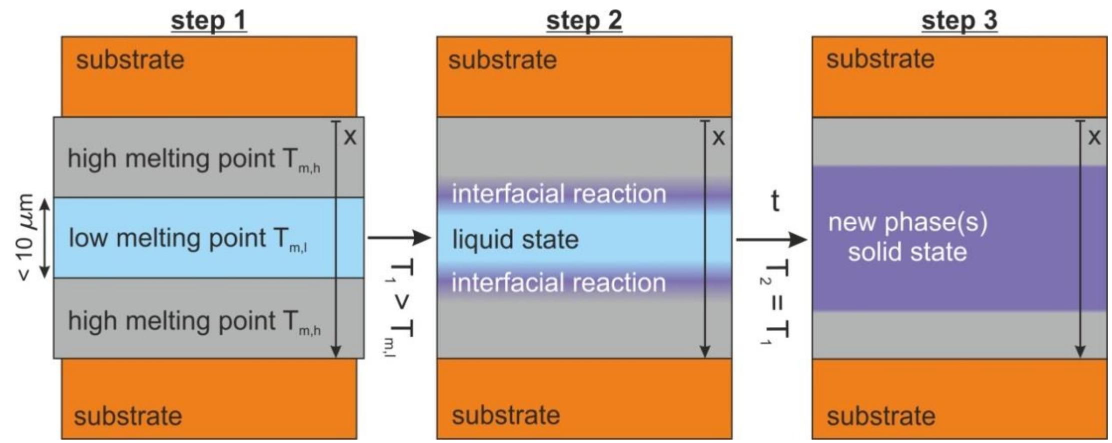
- Relative narrow (T, t)-processing windows
- Shrinkage porosity due to incomplete consumption of liquid Sn phase
- Kirkendall porosity (e.g. for CuSn)

Transient Liquid Phase (TLP) Bonding

EMPA Materials Science & Technology

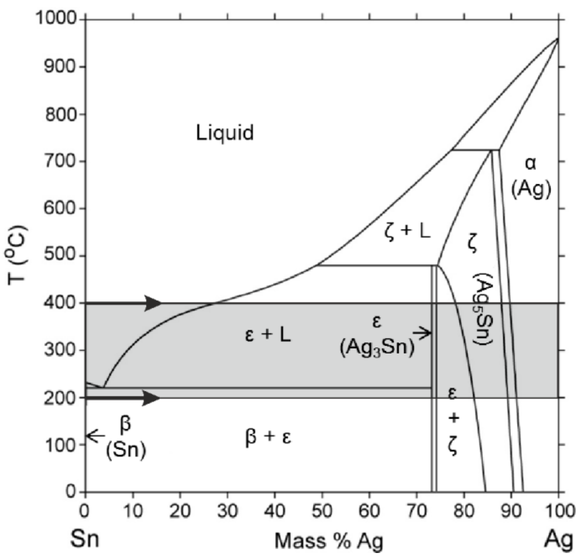
Advantages of the TLP process

- Fast joining < 250 ºC
- Operation >> 250 ºC



Basic Principles of the TLP process

Example: Ag-Sn and Ni-Sn TLP bonding

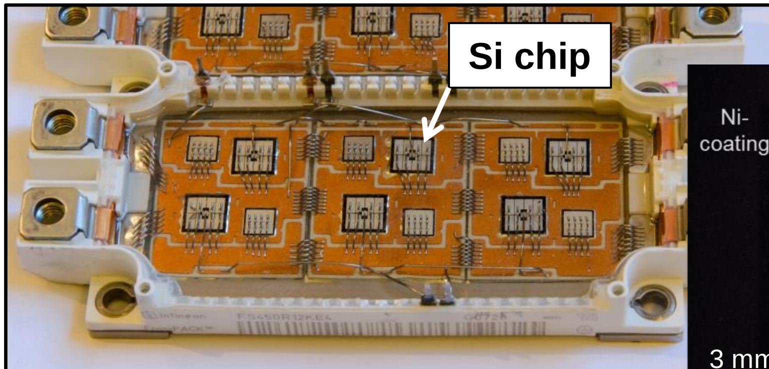


- ✓ Ag-Sn & Ni-Sn: 235 °C ≤ $T_{process}$ ≤ 300 °C
- ✓ Ag-Sn: formation of Ag_3Sn (ε) with T_m = 480°C
- ✓ Ni-Sn: formation of Ni_3Sn_4 with T_m = 794.5 °C

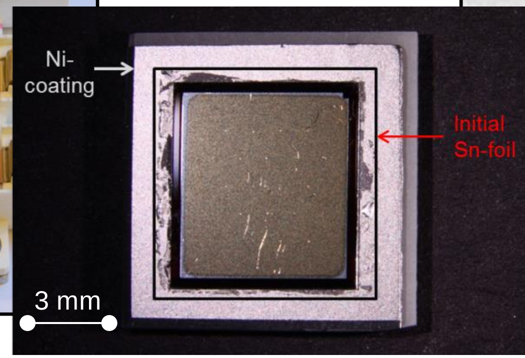
Transient Liquid Phase (TLP) Bonding

EMPA Materials Science & Technology

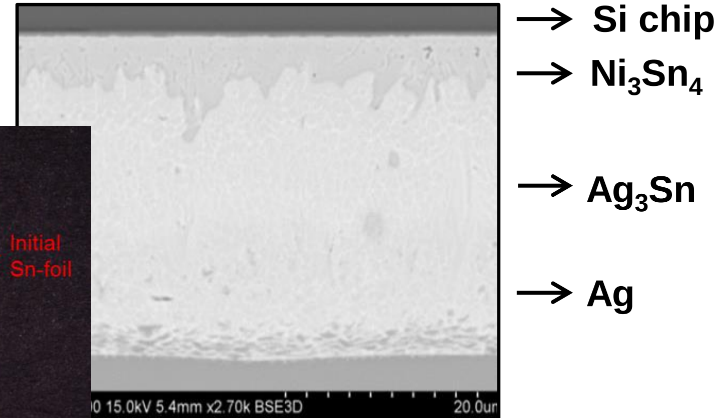
Ag-Sn TLP bonding for power electronics



Full IGBT module [source: Infineon]

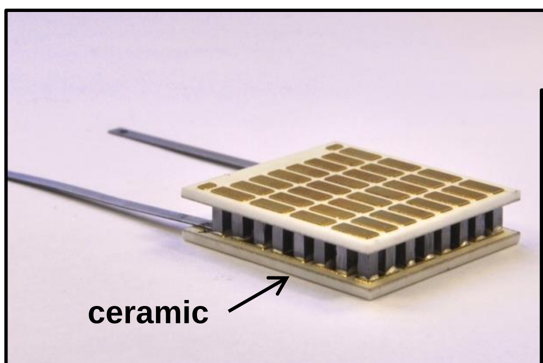


TLP-bonded Si chip [bonded @ Empa]

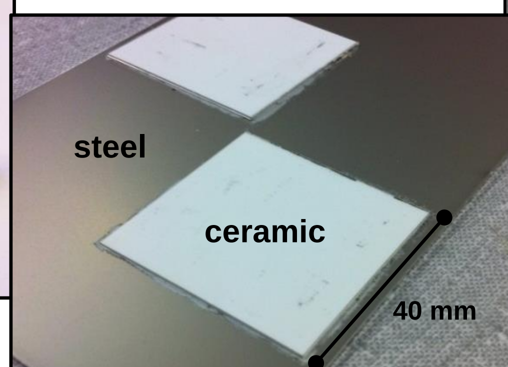


Cross- section of Ag-Sn TLP bond

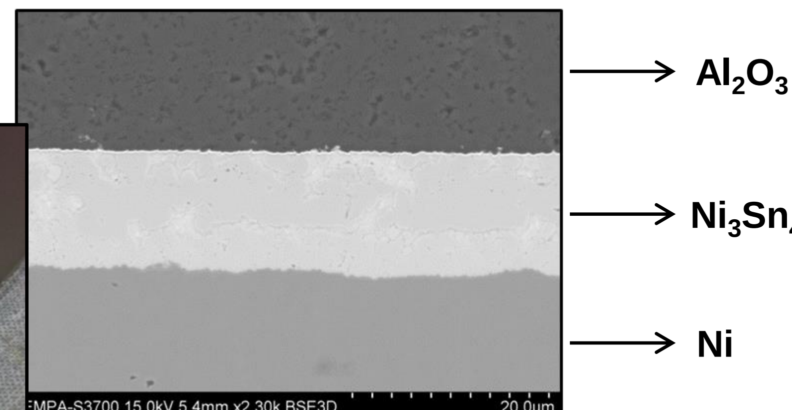
Ni-Sn TLP bonding for automotive applications



Thermoelectric module for exhaust applications



Large-area TLP bond [bonded @ Empa]



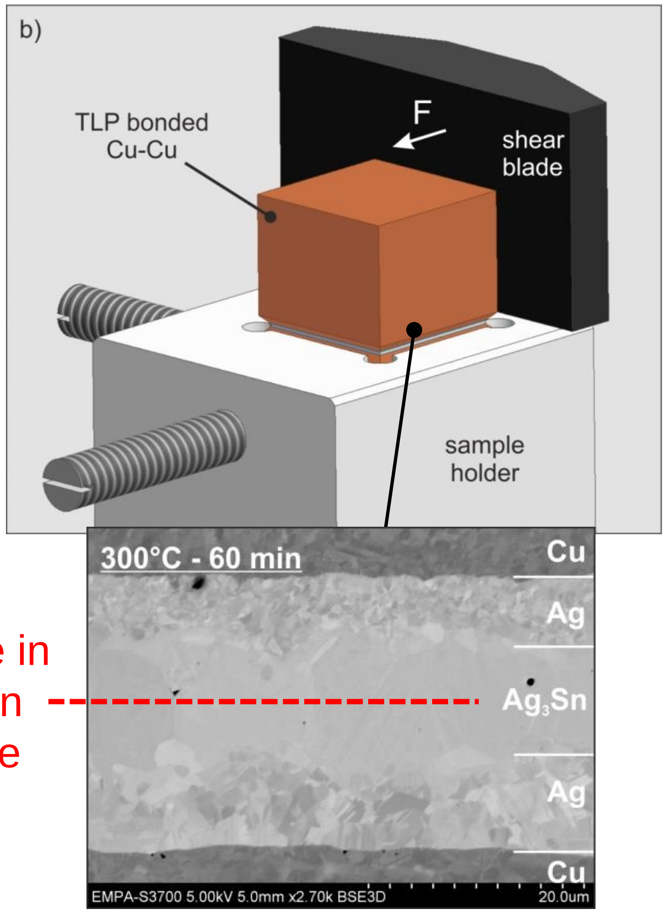
Cross-section of Ni-Sn TLP bond

Mechanical Integrity of TLP Joints

EMPA Materials Science & Technology

Shear strength of Ag-Sn TLP bonded Cu-Cu joints (no CTE mismatch)

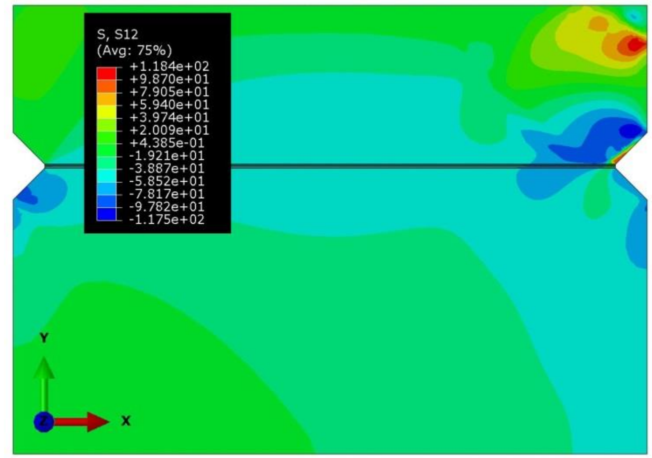
Experimental

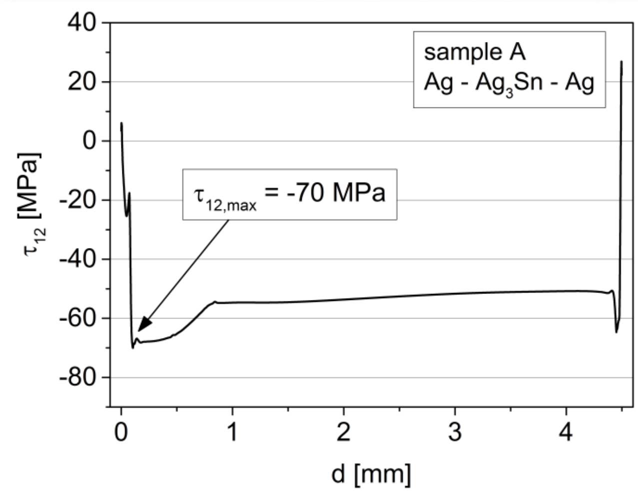


Failure in Ag_3Sn phase

$$\tau_{mean} = 60.7 \pm 7 \text{ MPa } (M = 0.5 \text{ Nm})$$

Finite-Element Modelling



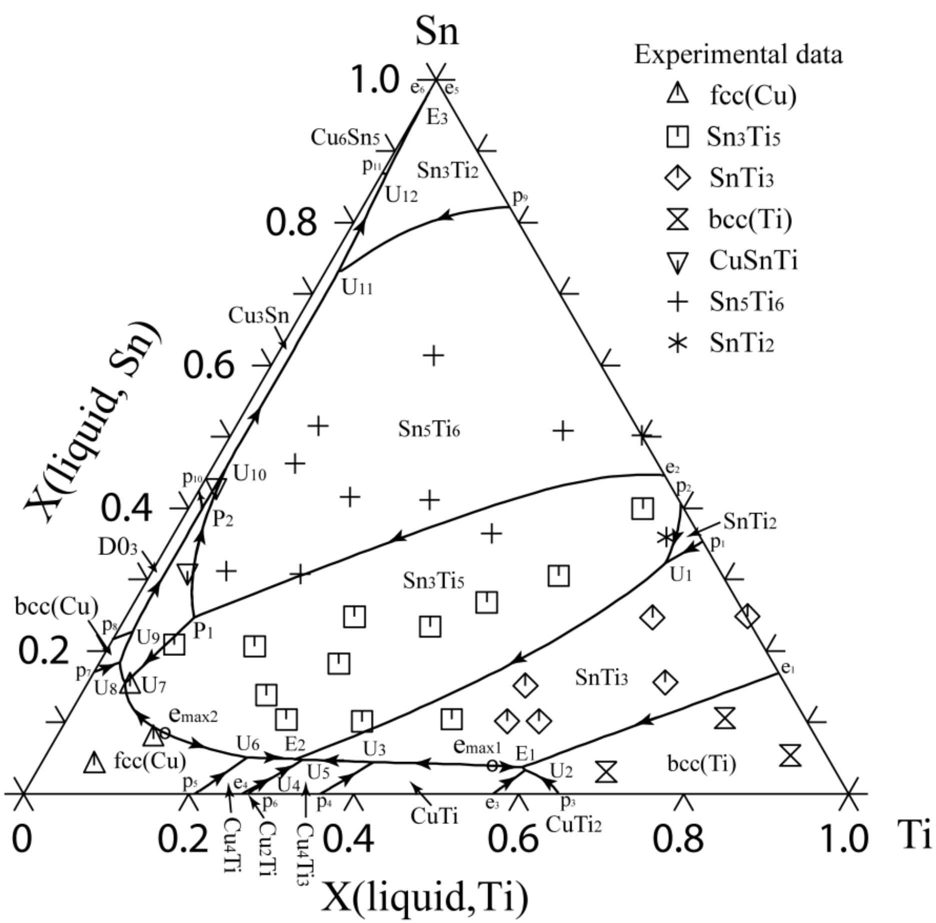


$$\tau_{crit,loc} = 70 \text{ MPa}$$

Nano-Joining Technologies

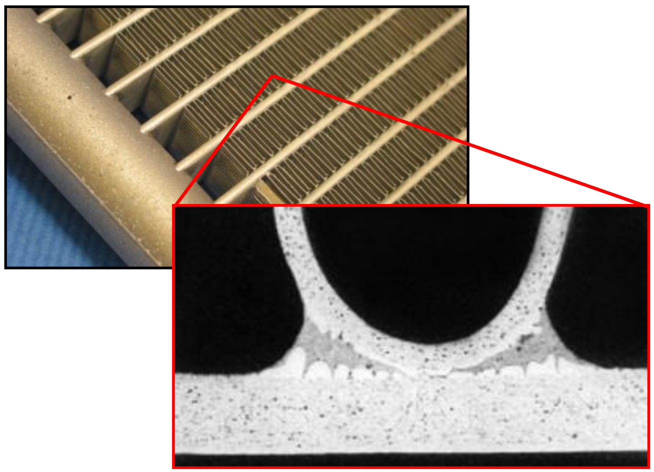
Conventional brazing and soldering technologies rely on Bulk Alloy Design

to reduce eutectic melting points, promote wetting and optimize interface bond strengths.



Liquidus projection of the Cu-Sn-Ti diagram (by CALPHAD methods)

Joining of diamond or c-BN for high-performance cutting tools



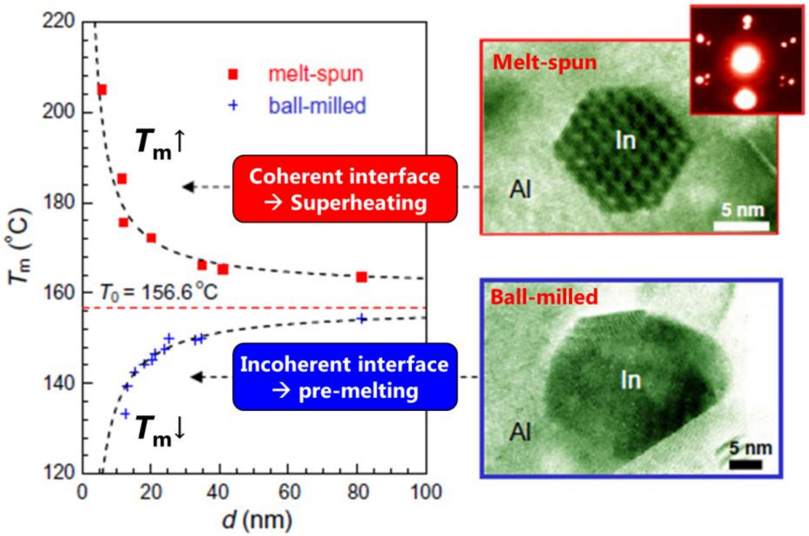
Joint assemblies in Al heat exchangers for automotive industries

Nano-Joining Technologies

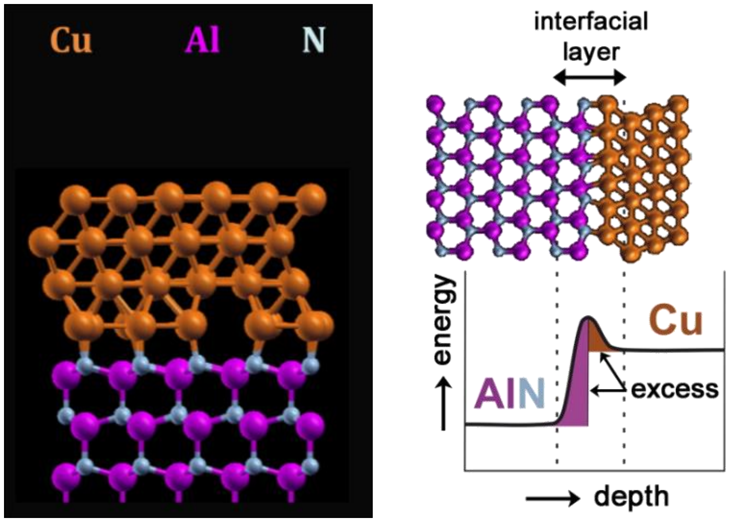
EMPA Materials Science & Technology

Nano-joining technologies are based on Nanostructured Filler Design

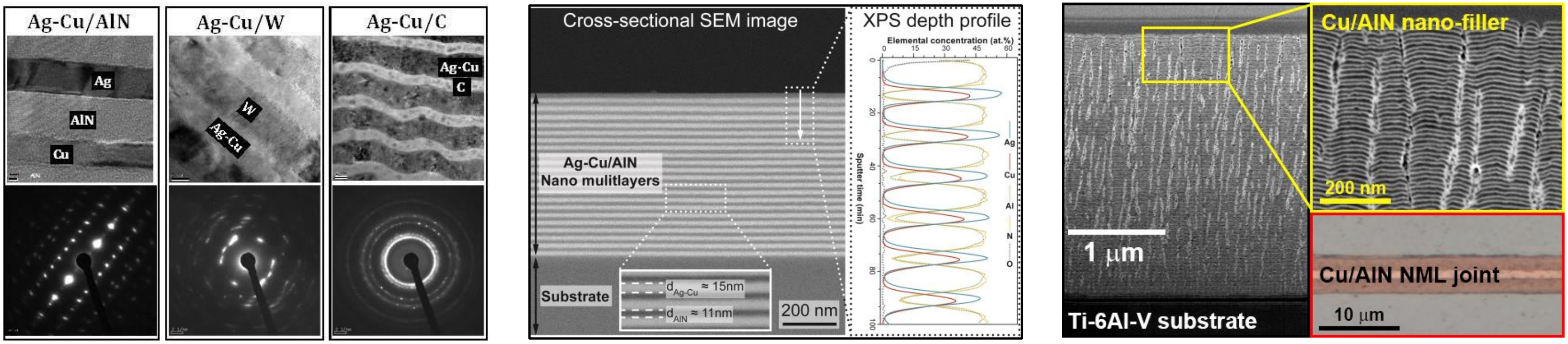
to tailor pre-melting, wetting and interfacial reaction kinetics by exploiting nano-scale effects



Interface engineering to promote interfacial pre-melting
[source: Lu & Jin, Curr. Opin. Solid State Mater. Sci. 5 (2001) 39]



Multi-scale modelling of defect structures and atomic mobilities at semi-coherent and incoherent interfaces [Empa]

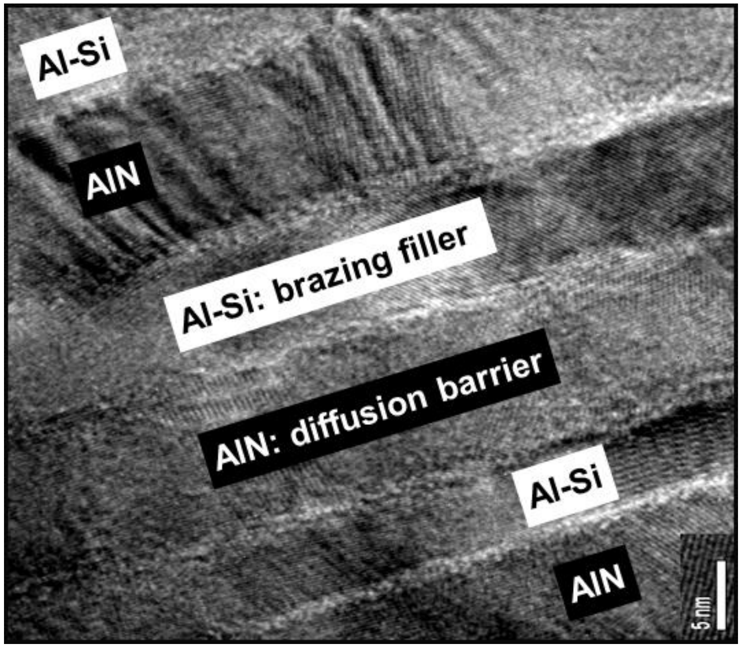


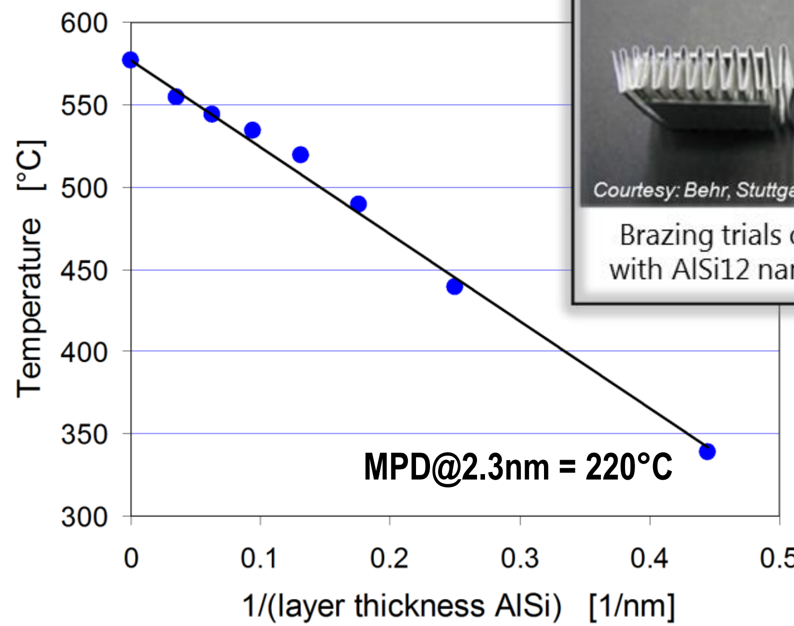
Research @ Empa: Fabrication and microstructural characterization of nano-mutlilayered brazing fillers for novel low-temperature joining applications

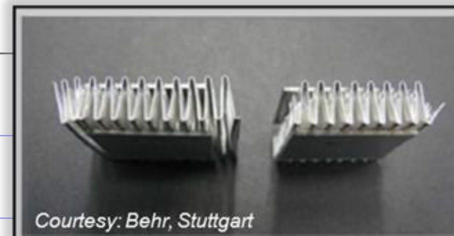
Nano-Joining Technologies

EMPA Materials Science & Technology

<u>Example:</u> AlSi-AlN nano-fillers for low-temperature brazing of Al alloys (Patent DE102008050433.5)







Brazing trials of Al segments with AlSi12 nanofiller at 580°C

Ultra-thin Al-Si films sandwiched between inert AlN diffusion barriers exhibit size-dependent melting point depression (MPD)

<u>Recent references on nano-joining research @ Empa</u>

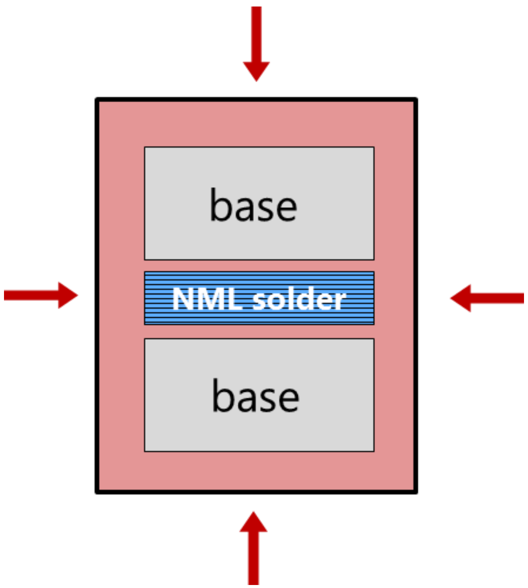
- *Copper-Based Nanostructured Coatings for Low-Temperature Brazing Applications*, Materials Transactions (2015).
- *Structural evolution of Ag-Cu nano-alloys confined between AlN nano-layers upon fast heating*, Physical Chemistry Chemical Physics (2015)
- *Interfacial design for joining technologies – An historical perspective*, Journal of Materials Engineering and Performance 23 (2014) 1608.

Reactive Nano-Foil Technologies

EMPA
Materials Science & Technology

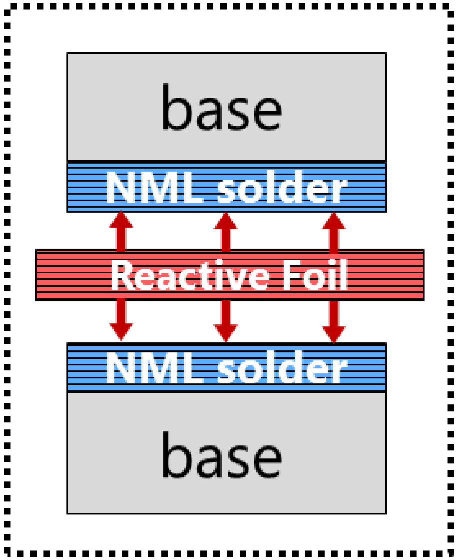
Combining nano-structured brazing fillers with reactive nano-foil technologies

CONVENTIONAL APPROACH



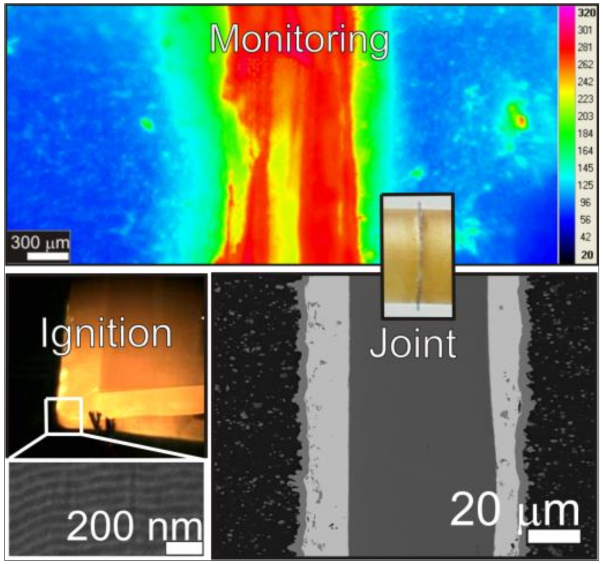
EXTERNAL HEAT SOURCE
(conventional furnace)

NOVEL APPROACH



INTERNAL HEAT SOURCE
(reactive nano-foil)

JOINING using reactive nanofoils @ Empa



Development and application of reactive
nano-foil technologies @ Empa

Advantages of reactive foil joining technologies

- No furnace needed!
- Fast joining at room-temperature in air or shielding gas.
- Heat is localized to bonded interface only, thus allowing joining of heat-sensitive materials

Reactive Nano-Foil Technologies

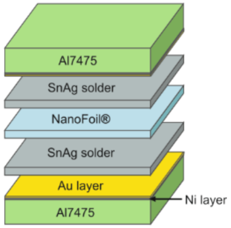
EMPA Materials Science & Technology

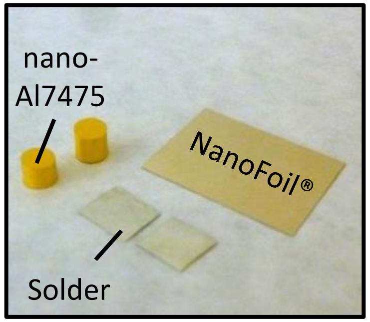
Example: Joining of nano-Aluminium using reactive Nano-Foil® technology

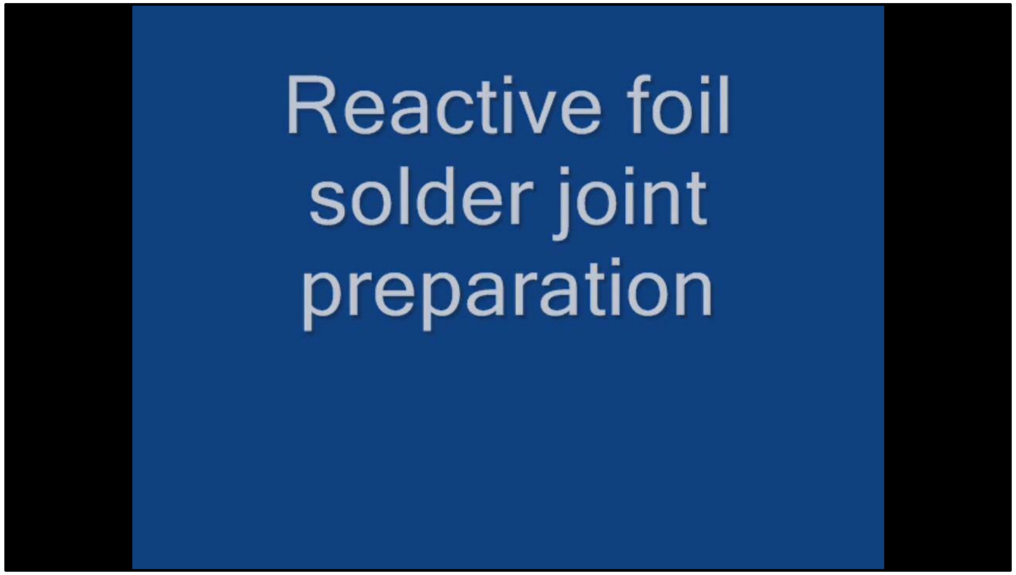
PREPARATION

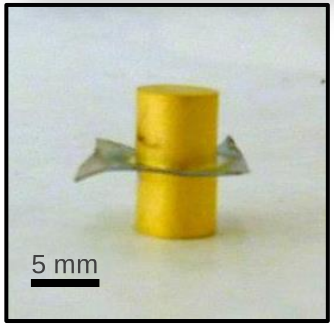
JOINING PROCEDURE

JOINT









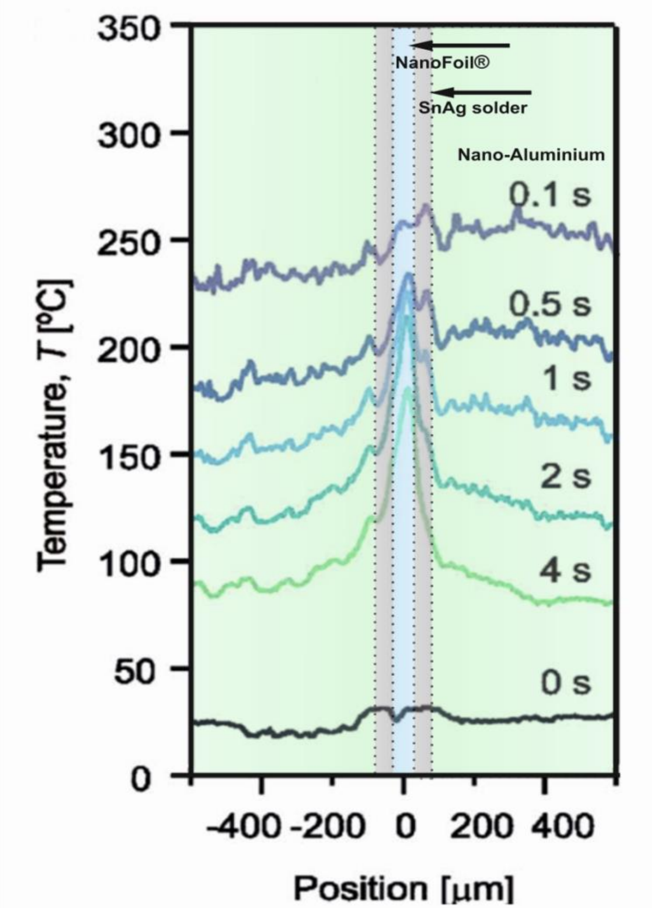
Process characteristics

- Ni and Al nanolayers react to form Ni_3Al and/or NiAl (heat of reaction up to -52 kJ/mol).
- Local ignition at room temperature with electrical spark, laser pulse or hot filament.
- Self-propagating reaction front with a speed up to 30 m/s.

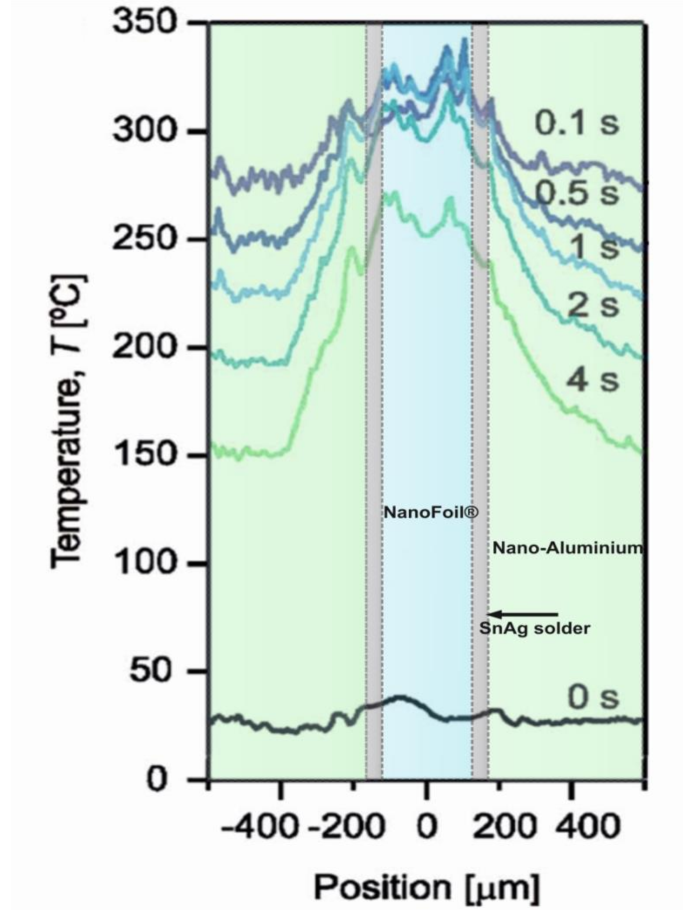
Reactive Nano-Foil Technologies

EMPA
Materials Science & Technology

<u>Example:</u> Joining of nano-Aluminium using reactive Nano-Foil® technology



60 microns foil



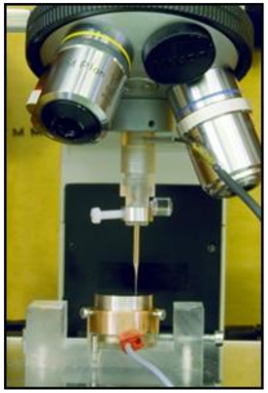
250 microns foil

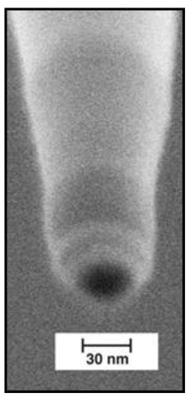
No heat affect on nano Al base material

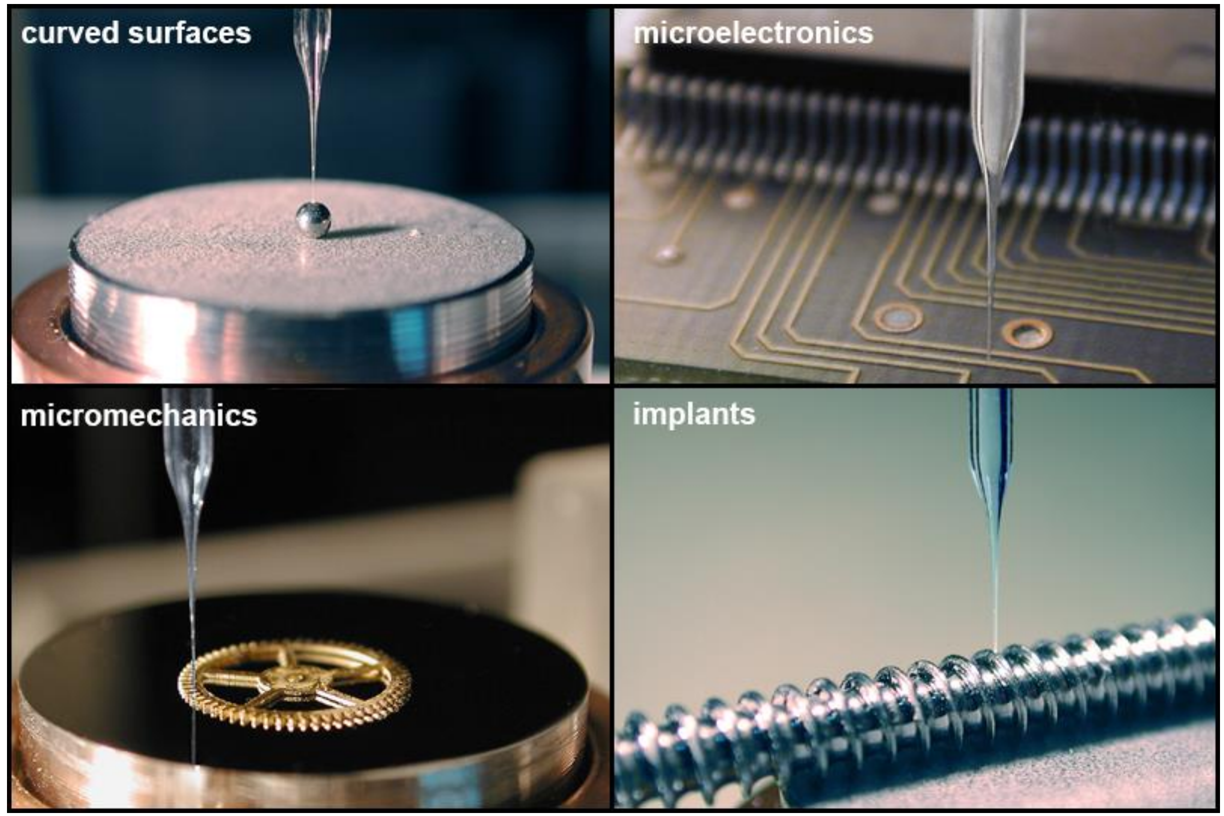
Heat affected zone < 200 µm

Chemical integrity of joint assemblies

EMPA
Materials Science & Technology







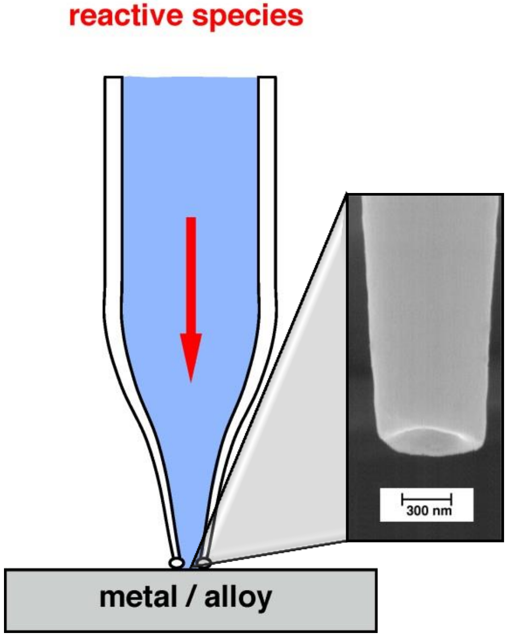
In-house developed micro-capillary electrochemical setups can:

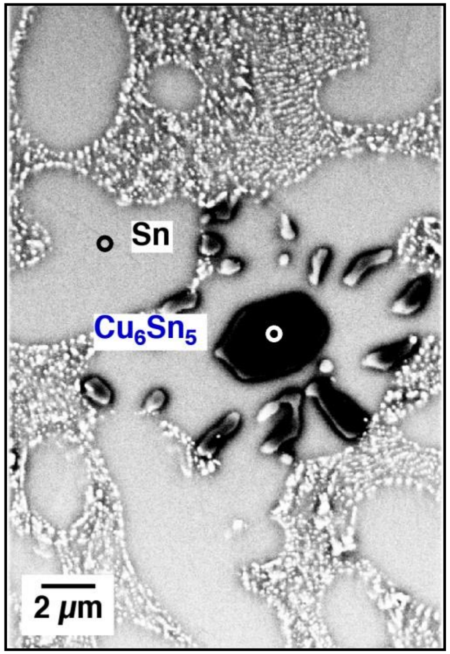
- Compare corrosion-susceptibility of different microstructural features in joint zone.
- Determine corrosion rate of the most susceptible microstructural feature in joint zone.
- Identifying the underlying corrosion mechanisms in different harsh environments.

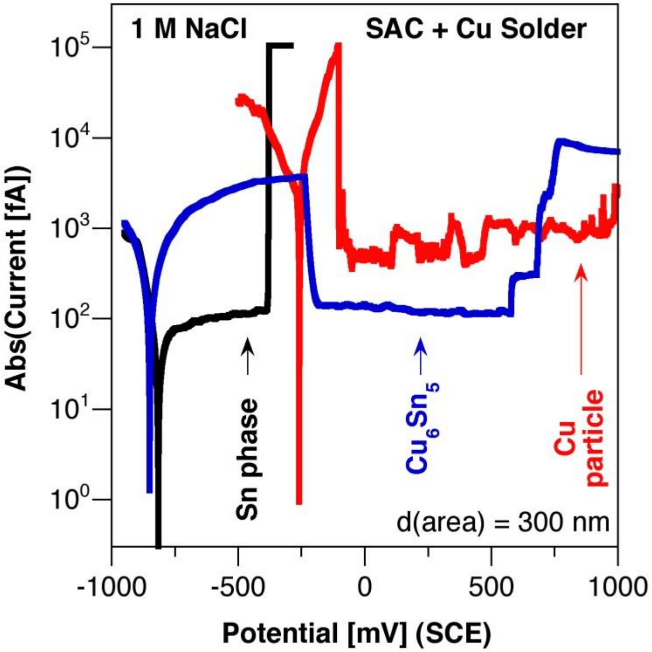
Ref: Suter at al, Electrochim. Acta 42 (1997) 3275

Chemical integrity of joint assemblies

Corrosion resistance of Cu-nanoparticle-reinforced lead-free Sn-Ag-Cu solders







Electrochemical polarization curves, as measured with 300 nm glass-capillary filled with 1 molar NaCl solution on various phases of the Cu-particle-reinforced lead-free Sn-Ag-Cu solder.

- Cu particles are (slightly) active and very noble.
- Sn-phase and Cu_6Sn_5 particles are more passive.

<u>Conclusion:</u> Cu nano-particles can act as local galvanic element, whereas Cu_6Sn_5 particles do not act as local galvanic element. → Cu-nanoparticles should fully react during soldering!

Vielen Dank für Ihre Aufmerksamkeit
Thank you for your attention
Merci pour votre attention

EMPA
Materials Science & Technology

Acknowledgements

Staff:

Jolanta Janczak-Rusch, Christian Leinenbach, Patrik Schmutz

Empa-Colleagues:

Vincent Bissig, Claudia Cancellieri, Mirco Chiodi, Hans Rudolf Elsener, Roland Hauert, Jacob Kübler, Joanna Lipecka, Adrian Lis, Remi Longtin, Frank Moszner, Jörg Patscheider,Thomas Suter.

Contact details

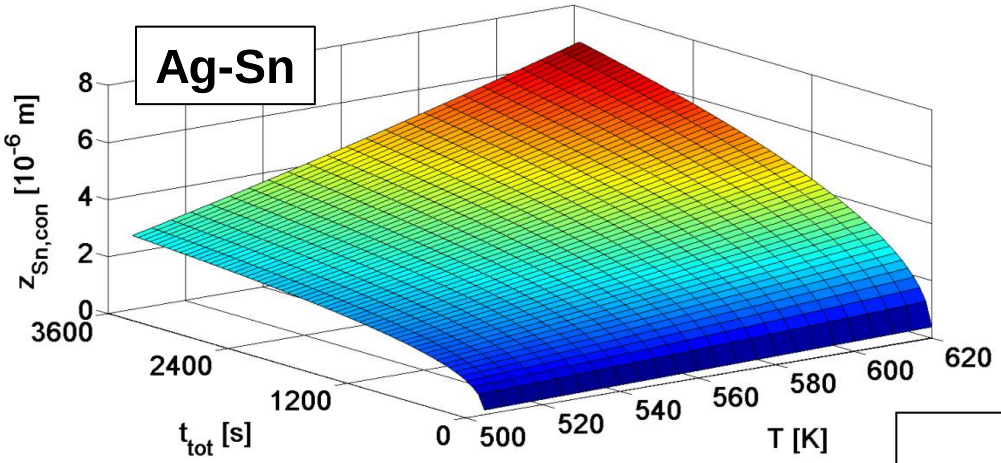
Dr. Lars P.H. Jeurgens (lars.jeurgens@empa.ch)

Homepage: www.empa.ch/Abt202

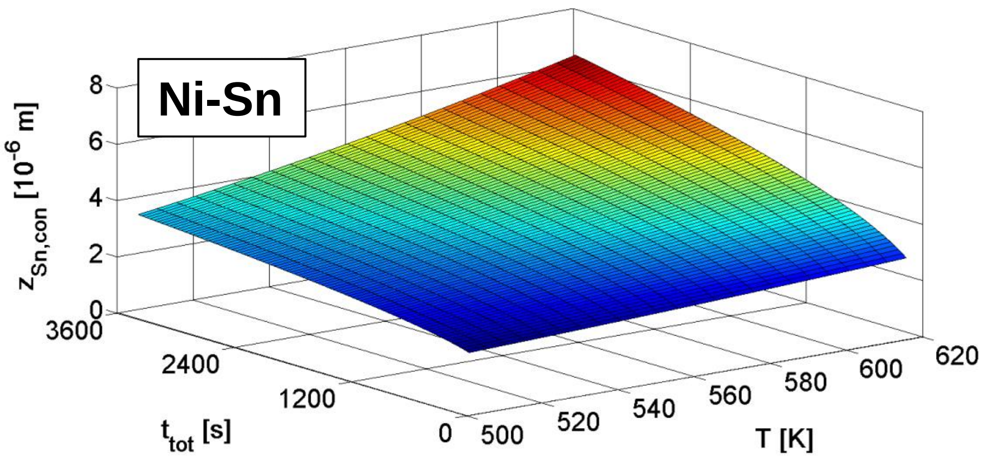
Transient Liquid Phase (TLP) Bonding

EMPA
Materials Science & Technology

Constructed Sn-consumption maps



/A. Lis et al., J All Compd 617 (2014) 763/



Example for 7 µm Sn-foil

Ag_3Sn	235°C → 80 min
	300°C → 20 min
Ni_3Sn_4	235°C → 50 min
	300°C → 10 min

$$z_{Sn,con}(T,t) = \left(\frac{\psi}{1+\psi}\right)\sqrt{k_{0,i}\cdot\exp\left(-\frac{Q_i}{RT}\right)}\cdot\sqrt{t}$$

Sn consumption factor — Arrhenius

with $\psi = \dfrac{(M(Y)\cdot y)/\rho(Y))}{(M(X)\cdot x/\rho(X))}$

M – molar mass
ρ – density
x,y – stochiometric number

Reactive Nano-Foil Technologies

Materials Science & Technology

System	Enthalpy of formation (kJ•mol^{-1})	Energy Density (kJ•cm^{-3})	RT ductility	Adiabatic reaction temp.(°C)	Ref.
Pt/Al	-100	1451	-	2800	*McAlister 1986*
Ni/Zr	-51	1025	-		*Nash 1984*
Ru/Al	-62	1000	✓		*Jung 1992*
Ni/Al	-59	861	-	1639	*Kleppa 1994* *Huang 1998*
Co/Al	-55	800	-		*Kleppa 1994*
Ti/Al	-40	788	-	1227	*Schuster 2006*
Y/Ag	-27	771	✓		*Colinet 1995*
Ni/Ti	-34	563	✓	1355	
Y/Cu	-19	506	✓		*Colinet 1995*