Brazing Technology – Advances and Challenges

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Brazing in Chemnitz – a long history

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IBSC, Long Beach, California, USA
Brazing of aluminum heat exchangers

Development of brazing process
→ temperature gradient
→ heat treatment

Heat exchanger

Optimization of design for a better brazability

Microstructure of joint after heat treatment

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Brazing of metal ceramic joints with modified MMC fillers

Brazing process:
900°C, 10 min, 10⁻³ Pa

Active brazing joints:
ceramic / particle reinforced filler metals / steel

- Cu + Al₂O₃/Cu_chem
combined with
AgCuTi foil

- ZrO₂

- AgCuTi foil
- Al₂O₃ particles
- AgCuTi foil

- SiC

- ZrO₂
Cu-matrix-composites – Carbon-fiber reinforced

Cu / SnCu3 / Cu/Cf-50%

• insufficient wettability,
• high porosity with conventional solders

Cu / SnAg3Ti / Cu/Cf-50% and US support

• reaction with fibers as a result of
  - Ti alloying and
  - US support
SnAg3 + Ti

Alloying of Cu-matrix
↓
Melting point of solder increases
↓
Isothermal solidification

SnAg3Ti soldered to copper
T_{solder} = 260°C / 3 min / US support

Cu-matrix-composites – Carbon-fiber reinforced
Cu-matrix-composites – Carbon-fiber reinforced

Filler metal: B-Ag72 brazed on copper

Active brazing joint with B-Ag72 + Ti (3 wt%)

With Titanium as active element:
- improved wettability of fibers results in
- better infiltration of MMC
- pore-free brazed joints

\[ T_{\text{brazing}} : 950^\circ\text{C}/10\text{min} \]
Soldering with diamond particles

Utilization of special physical properties of composites

- good thermal conductivity of diamond
- in combination with copper low CTE
- application: heat sinks electronic components

Sintered copper with diamond layer soldered to copper (260°C / 3 min / 5 s with US support)
Al-matrix-composites – Al$_2$O$_3$-fiber reinforced

- filler metal application by thermal spraying
- good bonding of particles into the filler metal $\Rightarrow$ fibers are wetted
- partially unhinging of fibers outside of the matrix due to mechanical activation by US

$T_{\text{solder}} = 430^\circ C / 3 \text{ min} / \text{US support: 30 s}$
Al-matrix-composites – \( \text{Al}_2\text{O}_3 \)-fiber reinforced

\[ \text{Al} / \text{ZnAl3} / \text{Al/Al}_2\text{O}_3f-60\% \]

\[ T_{\text{solder}} = 370^\circ\text{C} / 3 \text{ min}/ \text{US support: 30 s} \]

- good bonding of fibers inside the filler metal \( \Rightarrow \) fibers are wetted
Magnesium soldering

Advantages of magnesium:
- low density (1.74 g/cm³)
- castability
- recyclability
- high specific strength
- machinability

- portable electronic devices
- aviation industry
- mechanical engineering
- car industry
Magnesium soldering

Mg40Zn60

Mg40Zn55Al5

Mg45Zn55

Mg40Zn55Al5

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Research today – the story goes on

Graph showing temperature vs. wt.-% (Zr, Ta)C with two lines labeled Tsoil and Tliq.

Diagram of a cross-section of a device with labels indicating solder, IGBT, Silicon, Diode, Copper, Sn-3.5Ag solder, Cu$_3$Sn, Cu$_6$Sn$_5$, and Cu substrate. SEM images of the indents are also shown.
Co-based brazing fillers for high temperature applications
Development of new brazing fillers

Results of DSC investigation

- 5 wt% (Zr,Ta)C
- Co-dendrites

- 10 wt% (Zr,Ta)C
- Near eutectic

- 15 wt% (Zr,Ta)C

- 20 wt% (Zr,Ta)C
- Primary carbides (Zr,Ta)C
Co-based brazing fillers for high temperature applications

Further alloying with Ti and adapting Zr- and Ta-contents provides melting temperatures below 1200 °C.
Arc brazing of aluminum matrix composites on stainless steel

Exhaust gas cooler for diesel engines

Increased strength and good ultimate strain

Joints with AMC

Lightweight constructions

Micrograph of AMC [*]

Used AMC

[**] Aerospace Metal Composites Ltd.: High Performance Metal Alloys & Composites. Guest lecture (2011)

Arc brazing of aluminum matrix composites on stainless steel

Welding of AMC and steel

Brazing of AMC and steel

Advantages
- Specific heat input
- Less intermetallics
- Cleaning of surface by arc
Arc brazing of aluminum matrix composites on stainless steel

Suitable filler system: Al-Ag-Cu

Ternary state transition diagram (at%) [Eff04]

Ternary eutectic
Al40Ag40Cu20 (wt%)

\( \Rightarrow T_{\text{Liq}} \approx 500^\circ \text{C} \)

\( \Rightarrow \) Stable elements for arc brazing

Microstructure (SEM) of ternary eutectic with lamellar/columnar structure
Arc brazing of aluminum matrix composites on stainless steel

Manufacturing of filler: Al40Ag40Cu20

Casted wires Ø 2 mm of Al40Ag20Cu
Arc brazing of aluminum matrix composites on stainless steel

Results of wetting tests

Micrograph (SEM) of wetting test on AMC (left) and stainless steel (right) with Al40Ag20Cu
Induction brazing of metal ceramic joints

Motivation

Energy efficiency

- dwindling resources
- increasing CO₂ emissions ⇒ climate protection
- rising energy prices ⇒ lowering of costs

Establish induction brazing as an energy-efficient alternative to conventional furnace-brazing processes

Furnace

- Indirect heating ⇒ heat transfer by radiation ⇒ surrounding system is heated
- Relatively high thermal losses
- Long process times

Induction

- Direct heating ⇒ direct heat production in the workpiece
- Energy is transformed almost without heat losses ⇒ high efficiency
- Very short process times
Induction brazing of metal ceramic joints

Realization of faster heating rates, shorter holding times, faster cooling rates

- **Different process management**
  - investigation of the influence of differing process management on the quality of the joints

- **Wetting of ceramic**
  - investigation of heating by thermal conduction through the filler metal or the metal
Induction brazing of metal ceramic joints

Different process management

Joints with $\text{Al}_2\text{O}_3$

FeNi42 / B-Ag72Ti / $\text{Al}_2\text{O}_3$

Bending Strength

When using $\text{Al}_2\text{O}_3$: Thermally induced residual stresses are important

Cooling rate has to be adjusted
Induction brazing of metal ceramic joints

Different process management

Joints with ZrO₂

FeNiCo29-18 / B-Ag72Ti / ZrO₂
Bending Strength

When using ZrO₂:
- Adhesion is important
- Holding time has to be adjusted
Joining at low temperatures by using nanoparticles

**Motivation**

Utilization of the decreased melting and sintering temperature of nanoparticles for joining at low temperatures

**Melting temperature of silver nanoparticles:**

Joining at low temperatures by using nanoparticles

**Advantage:** After melting of the nanoparticles, the material behaves like the bulk material

⇒ **High-strength and temperature-resistant joints can be produced at low temperature**

Potential for the joining of:
- temperature-sensitive components in electronic applications
- mixed joints (aluminum-steel)
- materials with different thermal expansion coefficients (metal-ceramic)
- high-performance materials (with adapted and optimized microstructure)
Joining at low temperatures by using nanoparticles

Strength behavior of joints with copper

**Substrate:**
EN: Cu-ETP,
DIN material number: 2.0060

Joining area:
9 mm x 7.5 mm
Joining at low temperatures by using nanoparticles

The strength values of conventional brazed joints can be exceeded

Ag Nanopaste:
different pressures,
300°C, 10 min

Soldering:
SnCu3
300°C, 10 min

Brazing:
AgCu28
780°C, 10 min
Reliable soldered joints for power electronics in renewable energy systems

**Eutectic Sn-3.5Ag solder:**
- lead-free solder (alternative)
- high melting temperature
- good mechanical properties

Application fields:
- wind energy, solar power

Cross section of the layers in IGBT power module

IGBT power module
Determination of mechanical characteristics of the solder layers

Reliable soldered joints for power electronics in renewable energy systems

Light microscopy image of the chip soldered joint

SEM images of the indents

Graph showing elastic indentation modulus and indentation hardness for different phases:
- Eutectic
- β-Sn
- Ag$_3$Sn
- Cu$_5$Sn$_5$
- Cu
Reliable soldered joints for power electronics in renewable energy systems

**Active power cycling test**
- number of power cycles
- thermal resistance
- forward voltage

**Interaction**

**Materials**
- material characteristics
- crack initiation
- crack progression

**Simulation**

**Model of lifetime estimation**

*made by LEEMV*

*made by LVW*
Reliable soldered joints for power electronics in renewable energy systems

Active power cycling test: Disruption of solders due to temperature changes

now: slow power cycle $\rightarrow$ cracking at the chip edge
new: rapid power cycle $\rightarrow$ cracking in the chip middle

180000 cycles

SAM image of the chip soldered joint

SEM image, cracking in the chip soldered joint (middle), after 130000 cycles
Corrosion behavior of brazed plate heat exchangers

Ni-based fillers

- commercially used since the 1950s
- brazing in vacuum and inert atmosphere
- brazing temperature 890°C … 1190°C
- common base materials: steel, Ni-based alloys
- high joining strength
- corrosion resistance

- Amendment of the drinking water directive
  ⇒ Reduction of the permissible Ni-ion content in drinking water from 50 µg/l to 20 µg/l (1st January 2003)
Corrosion behavior of brazed plate heat exchangers

Dynamic rig test according to DIN EN 15664-1

- Pipes 1.4401 (V4A, X4CrNiMo17-12-2)
- Reference line (1.4404, V4A)
- Test lines
- Ni 650
- Ni 710
- B-Ni60CrPSi

- Test pieces
- Flow rate measurement
- Back pressure valve
- Outlet valve

sample
Corrosion behavior of brazed plate heat exchangers

Release of Ni ions vs. testing time

Ni-based filler metals Ni 650, NI 710 and B-Ni60CrPSi are consistent with the Drinking Water Directive
Resistance brazing of AMC and aluminum alloys

- Short heating times and local heat treatment
- Ultrasonic treatment fluxless wetting
- Geometry of contact surface influences electrical resistance

\[ Q = I^2 \cdot R \cdot t \]

- \( Q \): heat quantity [J]
- \( I \): current [A]
- \( R \): electrical resistance [Ω]
- \( t \): time [s]

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<tr>
<td>Duration of treatment</td>
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</table>
Resistance brazing of AMC and aluminum alloys

Optimization of the geometry

Used base materials:
- AA2017
- AA2017 + 10 vol.% (Al₂O₃)ₚ

Filler:
- ZnAl5 (95 wt.% Zn, 5 wt.% Al), joining temperature 400 – 420°C
Resistance brazing of AMC and aluminum alloys

- Critical pores
- Stress concentration
- Crack initiation
- Uncritical pores
- Defined gap
- Fitting is more useful

Base material
Pores
Solder fillet

Defined gap
Base material
Pores, voids
Solder fillet
Future work
High-temperature active fillers with carbides

Development of Co based fillers for metal/ceramic brazing

- Eutectic
- Co matrix
- Carbides
- Reaction zone
- Ceramic (Al₂O₃)
Metal migration of Cu brazed Plate Heat Exchangers (PHE)

- Pitting corrosion
- Intermetallics
- Corrosion at grain boundaries

Base material: 1.4404

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Atomization of filler metal for brazing and deposition welding

Atomization

Powder characterization

Smelting
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