Brazing and Vacuum Brazing
Workshop on Pipe Joining Techniques for the ATLAS and CMS Tracker Upgrades
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Soldering/Brazing

Joining of two components with a brazing filler material (BFM), whose liquidus temperature is below the melting point/range of any joined component → No melting of the component material

**Soldering**

\[ T_{l_{FM}} < 450^\circ C \]

- Typically used SnAg3.5 (ISO 9453 S-Sn96Ag4; \( T_{liq} = 221^\circ C \)), \( R_m \approx 25 \text{ MPa} \)

**Brazing**

\[ T_{l_{FM}} > 450^\circ C \]

- Typically Ag-based filler metals, i.e. AWS BAg-7 (\( T_{liq} = 650^\circ C \)), \( R_m \approx 400 \text{ MPa} \)

Soldering of stainless steel/copper:
- Typically used SnAg3.5 (ISO 9453 S-Sn96Ag4; \( T_{liq} = 221^\circ C \)), \( R_m \approx 25 \text{ MPa} \)

Brazing at high temperature of stainless steel/copper:
- Typically Ag-based filler metals, i.e. AWS BAg-7 (\( T_{liq} = 650^\circ C \)), \( R_m \approx 400 \text{ MPa} \)
Brazing Technologies

Classified by heating technology:

- **Brazing using liquids for heating**
  - DIP brazing
  - Salt-bath brazing
  - Flux-bath brazing

- **Flame brazing**
  - Flame brazing

- **Brazing with an electric arc**
  - Manual metal arc brazing
  - Tungsten inert-gas brazing
  - Plasma gas brazing

- **Brazing using radiation**
  - Laser beam brazing
  - Electron beam brazing
  - Induction brazing in air
  - Induction brazing in a protective atmosphere
  - Indirect resistance brazing
  - Direct resistance brazing
  - Furnace brazing with flux
  - Furnace brazing in reducing shielding gas
  - Furnace brazing in inert shielding gas
  - Furnace brazing in vacuum

ISO 857-2
Brazing Technologies

Manual Brazing at Atmosphere

• Heat Sources: Flame Torch (Acetylene), Induction, (Plasma, Arc…)

• Working Temperature of common filler metals: 600-800°C
  • Steel/Stainless Steel, Copper Alloys: I.e. AgCuZnSn (650°C, )
  • Application of flux necessary to remove surface oxides
  • Brazing of tube fittings:
    Lap joints (5-10 mm overlap, rule is min. 3x \( t_{wall} \))
    Gap clearance of joint ca. 0.1-0.2 mm on diameter
    Manual process, individual qualification of personnel necessary
Brazing Technologies

**Manual Brazing at Atmosphere**

**Preparation of components:**

- Cleaning/Etching (Surface treatment)
- Application of flux on brazed surfaces
- Assembly and possible inertisation for tubes (Ar-flush inside) to avoid oxidation on the inner wall
- Brazing material normally applied as rods/wires
- Brazing with avoiding overheating (can change viscosity of filler, incrusting of flux)

**Post treatment:**

- Cleaning/removal of flux from components. Mechanically and cleaning with detergent/warm water (surface treatment)
  
  - Flux contains components as KF, Borates etc. -> corrosive!
- Visual inspection

**Precautions:**

- Ventilation of fumes (flux) which can condense on surrounding surfaces
- Environment of torch flame
Brazing Technologies

Manual Brazing at Atmosphere

Joining of ss-sleeves to 5 m-Cu-OF tubes

Visual inspection (endoscopy)

Qualification samples
Vacuum Brazing

General features of vacuum brazing

Assemblies brazed in vacuum chambers (10^{-2} mbar…10^{-7} mbar)

Parts have to be clean (outgassing, pollution) and principally oxide-free (wetting properties)

Heating performed by radiation, induction, (laser, microwave, EB..)
→ most common technology: vacuum furnaces with resistor heaters

Use of vacuum compatible filler-materials (no volatile components at corresponding brazing temperatures)
→ most common BFM for vacuum brazing:
  → Silver-Copper alloys (780-950°C)
  → Gold-Copper alloys (950-1050°C)
  → Nickel-based alloys (1000-1200°C)
Vacuum Brazing

Advantages of vacuum brazing

No flux used/necessary
No residual fluxing agents have to be removed/cleaned after process, no risk of corrosion induced by remaining flux (mostly acids containing fluorides and/or chlorides)

Particular materials can be de-oxidized under vacuum and high temperature (i.e. copper)
Depending on thermodynamic stability of the specific oxide-scale

Brazed parts stay clean and no oxidation occurs during brazing process
Besides flux has not to be removed, the surfaces stay clean and metallic (applications for UHV and RF-cavities)

Specifically for furnace brazing:
Low distortion of assembled pieces due to homogeneously heated parts
High precision assemblies maintain their geometry and alignment
Vacuum Brazing

Disadvantages of vacuum brazing

General high costs:
- vacuum furnace equipment
- only batch production possible
- preparation of all assembly parts necessary (surface treatment)
- vacuum grade filler materials more expensive
- long brazing cycles (up to few days from cold to cold)

Specifically for furnace brazing:
Complete assembly has to be heated
Due to high brazing temperatures material properties will be influenced by the heat treatment (annealing, grain growth, diffusion/precipitation)

Complex preparation
Fixed placement of filler material, fixed positioning of assembly parts has to be assured
Vacuum Brazing

Vacuum Furnace Brazing at CERN

- Cooled wall furnaces with ss-vacuum chamber
- HV-pumping groups to reach vacuum range of $10^{-6}$ mbar (oil-diffusion or turbomolecular pumps)
- All-metal hot zones with molybdenum resistive heaters and Mo/ss-thermal screens
- Horizontal and vertical configurations
- Surveillance of brazing processes with load thermocouples and furnace windows
- Max. temperatures up to 1300°C/1600°C
Production cycle of vacuum brazed parts

Design of vacuum brazed joints

- Materials choice has to be -besides functional requirements- as well in accordance with vacuum brazing needs, i.e.:
  - Copper with low oxygen-content mandatory (OF/OFE copper)
  - Thermal stress release of materials must be considered especially for high-accuracy (if necessary, usage of 3D-forged blanks (OFE-copper, 316LN stainless steel)
  - Materials/alloys must not contain volatile elements (high vacuum at brazing temperature), i.e. Zn, Mn, Cd etc…

- Adequate gap-clearance must be ensured by design and tolerances
  - Depending on the used BFM, certain gap clearances and surface roughness values for the areas to be brazed must be kept
  - For flat joints, planarity has to be tolerated according to max. gap requirements

- Design features for placement of BFM
  - Depending on form of applied BFM, i.e. wires (placed in grooves, chamfers), foils or paste

- Special cases
  - Metallization coatings for $\text{Al}_2\text{O}_3$-ceramics
  - Ni-plating etc…
Production cycle of vacuum brazed parts

Design of vacuum brazed joints

RF-switch (CLIC)
Copper (OFE) cavity with ss-flanges for pumping and waveguide-connection

924

planarity (on both sides to assure gap of max. 40 µm)

joining process acc. to EN ISO 4963

924

gap clearance (here: 10-50 µm)

Sharp edges to stop BFM-flow
Production cycle of vacuum brazed parts

Machining/tolerance requirements

• Gap tolerances have to be kept during brazing process (heat treatment)
  • Depending on part-geometry and material type, stress releasing heat treatments have to be foreseen before final machining
  • Example: Joint between metal-ceramic: Calculation of gap during brazing necessary. Small diameters may maintain a sufficiently small gap at the brazing temperature

• Machining between different brazing steps should be avoided
  • Risk of polluting parts surface makes subsequent cleaning and pickling necessary
  • In some cases, intermediate machining can’t be avoided
    • → Use of ethanol as lubricant for machining copper parts brazed with Ag-alloys
    • → Mask brazed joints and sensitive surfaces during machining and surface treatment
Production cycle of vacuum brazed parts

Surface treatment before brazing

- Due to the treatment under vacuum, parts have to be at least entirely degreased before brazing steps
- Oxide scale on metallic components have generally to be removed (i.e. by pickling)
- Special cases for (additional) surface treatments:
  - **Nickel-coating** (wood’s-strike) in ss-components for brazing with Ag/Cu-alloys (diffusion boundary, improved wettability)
  - **Silver-coating** (10-15 µm) for diffusion-brazing with copper
  - For some metals (i.e. Nb) special care has to be taken according to fast oxidation at ambient conditions (-> brazing within ca. 24 h after pickling)
Production cycle of vacuum brazed parts

Assembly and brazing procedure

- Vacuum brazing cycle
  - Loading furnace and pumping to high-vacuum at RT
  - Heating-program for brazing

![Diagram showing temperature profile during brazing process]
Examples for brazed parts at CERN

Copper/Copper - Stainless Steel/Copper

SS-flanges on copper tubes for LSS-chambers

Septum coil – copper coil integrally joined with copper- and ss-tubings

Typical filler materials used:
Ag72/Cu28 (eutectic, $T_{\text{brazed}}$: 780°C)
Ag68/Cu27/Pd5 ($T_{\text{brazed}}$: ca. 815°C)
Ag58/Cu32/Pd10 ($T_{\text{brazed}}$: ca. 855°C)...
Glidcop®-parts

Glidcop demands special attention due to high diffusion coefficient of Ag
For brazing with Ag-based filler materials, a diffusion layer has to be applied. This can be achieved by certain combinations of electroplated copper (H₂-diffusion) and nickel (barrier for Ag).
Examples for brazed parts at CERN

Stainless Steel, other alloys

Ss-tubes for NA62-detector cooling circuit
Vacuum chamber (Inconel)

Typical filler materials used:
Nicrobraz (Ni-based BFM, $T_{\text{braze}} \geq 1020^\circ\text{C}$)
Ag-based BFM as well usable ($T_{\text{braze}}: 780-950^\circ\text{C}$)
Examples for brazed parts at CERN

Ceramic Brazing

Copper rings in $\text{Al}_2\text{O}_3$ for LHC-couplers

$\text{Al}_2\text{O}_3$ RF-window in Ti-flange and Cu-tube for coupler

Kovar/Monel-plugs on ceramic (insulators)

Active brazing of Kovar-rings on AlN-tube (Linac4-source)

Typical filler materials used:

Ag/Cu-alloys for metallized ceramics

Active brazing filler materials - i.e. Cusil-ABA® ($\text{Ag}_63\text{Cu}_{35}\text{Ti}_2$, $T_{\text{braze}}: \geq 850^\circ\text{C}$)
Examples for brazed parts at CERN

Ceramic Brazing

Diffusion brazing of copper/Al$_2$O$_3$-joints

Silver deposition on metallized surface of ceramic component (ca. 15 µm)
Copper/Silver creates under contact eutectic liquid phase that joins the interface (external copper parts have to be deformed by i.e. Mo-wires)
Assembly of Capillaries for CMS Pixel Upgrade

Vacuum Brazing Assembly for Lines with Dielectrics

Inlets by ss-capillaries ($\Phi_{ss}1.6$ and $\Phi_{ss}2$)

**Assembly sequence:**

1. Brazing copper sleeves to capillary/tube
2. Brazing of VCR-connector (with nut) or welding fitting
3. Final assembly with dielectrics

Return-pipes in copper ($\Phi_{copper}5$)

Usage of three different BFM with decreasing melting range

ss-copper transition for subsequent orbital welding

Brazing to ceramic with Cu-sleeves
Assembly of Capillaries for CMS Pixel Upgrade

Vacuum Brazing Assembly for Lines with Dielectrics

Capillary to VCR-connector

- Avoiding of BFM close to opening (risk of plugging by filler)
- Limited quality control possible, qualification samples with metallographic evaluation

Copper-ss transitions

- Metalluric control and US-inspection on qualification samples

Real parts due to size not controlable by NDT

- Visual check
- Pressure/leak-check (100%)
Assembly of Capillaries for CMS Pixel Upgrade

Vacuum Brazing Assembly for Lines with Dielectrics

Ceramic to metal-transitions

- Problematic of mismatch in CTE -> Copper/Al₂O₃ up to Ø5 mm feasible with AgCu-alloys
- Thermal stresses on ceramic introduced by metallic part -> soft state of copper compensates stresses by plastic deformation
- Ceramics: Metallization on brazing interface necessary. Mo/Mn+Ni-coating realized by suppliers

Direct joining on ss-sleeves -> Cracking of ceramic!
Copper transitions maintain ceramic intact due to plastic deformation/lower youngs modulus
Assembly of Capillaries for CMS Pixel Upgrade

Vacuum Brazing Assembly for Lines with Dielectrics

Some Conclusions/Important points

- Tight tolerances between sleeves and tubes have to respected to allow reliable bonding – max. allowable gap clearance of ca. 50 µm for most common BFM (solder based)

- Surface treatment for joining surfaces and cleanliness for vacuum heat treatment mandatory

- Components used have to be HV-compatible

- Limited quality control due to small assemblies/bad accessibility -> qualification campaign
  - US-Inspection
  - Metallurgical investigation

- Proof tests by leak and pressure tests for 100% of the components strongly advisable
Vacuum Brazing Workshop at CERN

Equipment

**XERION2 (all metal)**
- working useful space:
  - Diameter (mm): 450
  - Depth (mm): 1600
- Temperature:
  - Max (°C): 1300
  - Normal working temperature range (°C): 200-1300
- Ultimate vacuum (mbar): $10^{-6}$
- Charge capacity (kg): 450

**TAV (all metal)**
- working useful space:
  - Diameter (mm): 650
  - Depth (mm): 2000
- Temperature:
  - Max (°C): 1350
  - Normal working temperature range (°C): 200-1200
- Ultimate vacuum (mbar): $10^{-7}$
- Charge capacity (kg): 750
Vacuum Brazing Workshop at CERN

Equipment

**PVA** (all metal)
- working useful space:
  - Diameter (mm): 650
  - Height (mm): 1750
- Temperature:
  - Max (°C): 1350
  - Normal working temperature range (°C): 200-1200
- Ultimate vacuum (mbar): $10^{-7}$
- Charge capacity (kg): 750

**DVM** (all metal)
- working useful space:
  - Diameter (mm): 400
  - Height (mm): 500
- Temperature:
  - Max (°C): 1600
  - Normal working temperature range (°C): 350-1300
- Ultimate vacuum (mbar): $10^{-7}$
**Equipment**

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<th><strong>VAS (all metal)</strong></th>
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| | 120 | 400 |
| | 200 | 500 |
| | 1600 | 1600 |
| | 200-1200 | 200-1600 |
| | 10^{-8} | 10^{-6} |
| | Vac., Ar, Ar/H₂, H₂ | Vac., Ar, Ar/H₂, H₂ |
Vacuum Brazing Workshop at CERN

Equipment

Additional:

- Induction-system (incl. vacuum chamber)
- Air furnaces