VACUUM BRAZING

Fritz Motschmann
CERN
fritz.motschmann@cern.ch

CERN | EN ENGINEERING DEPARTMENT

Agenda

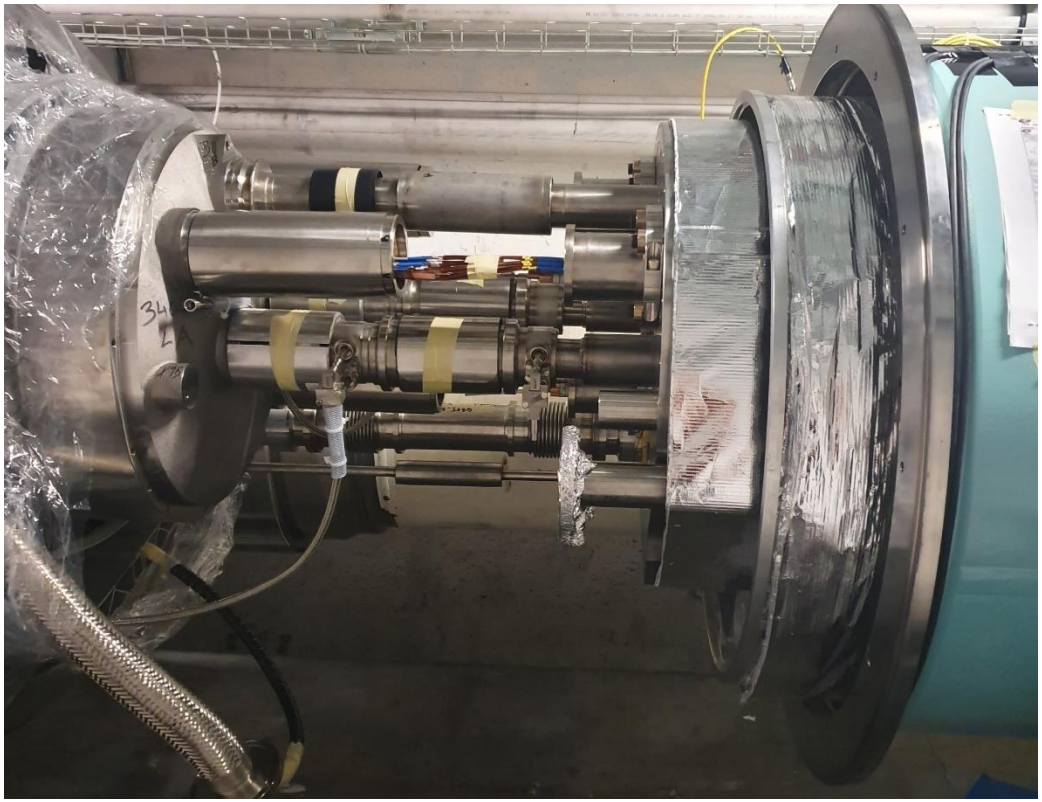
1. Brazing amongst joining processes
2. Physical principles of (vacuum) brazing
3. Fabrication cycle of vacuum brazed assemblies
4. Equipment and technical requirements
5. CERN-made examples
6. Conclusion

Agenda

1. Brazing amongst joining processes
2. Physical principles of (vacuum) brazing
3. Fabrication cycle of vacuum brazed assemblies
4. Equipment and technical requirements
5. CERN-made examples
6. Conclusion

Brazing amongst joining processes

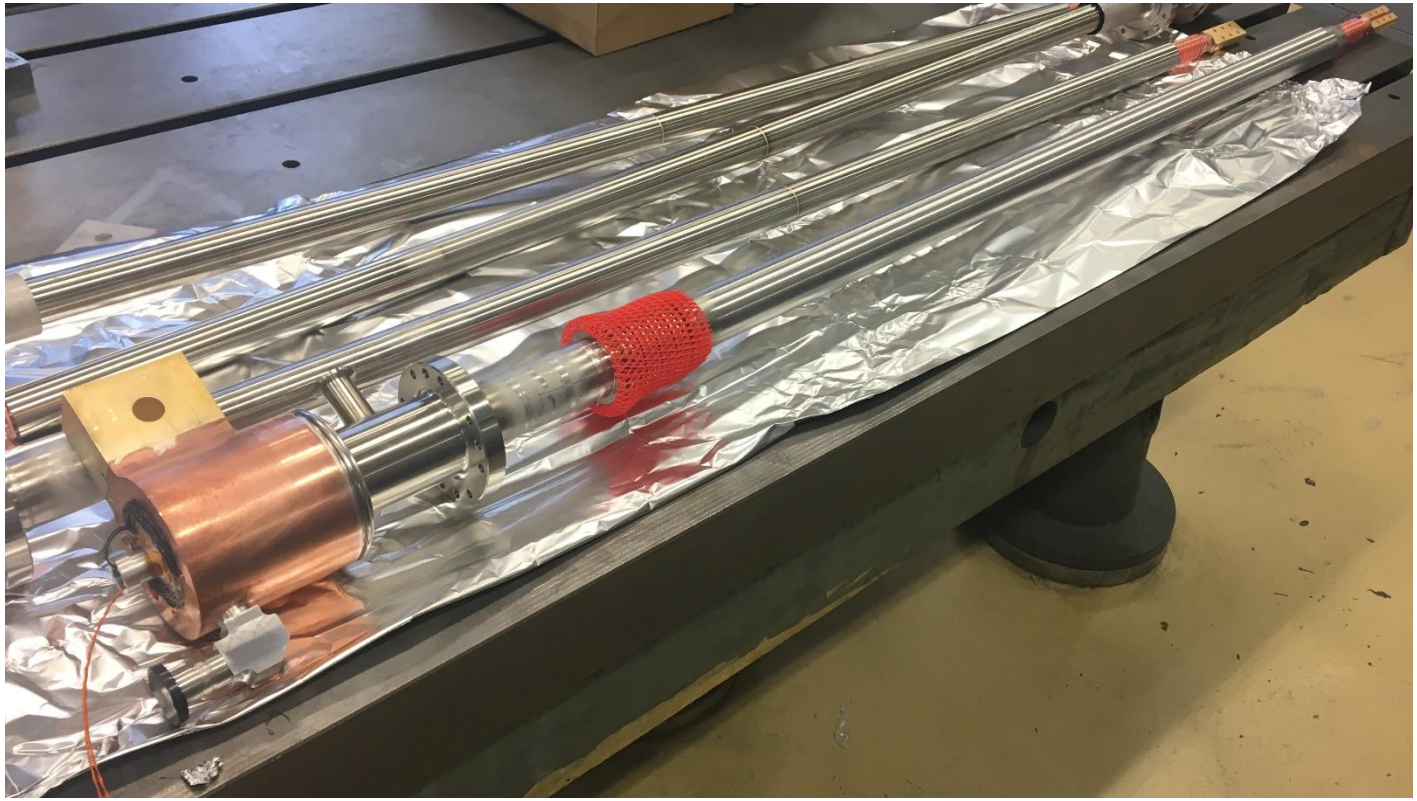
Metal Joining at CERN – The Forming and Welding-Section (EN-MME-FW)



LHC-Magnets Interconnection

Brazing amongst joining processes

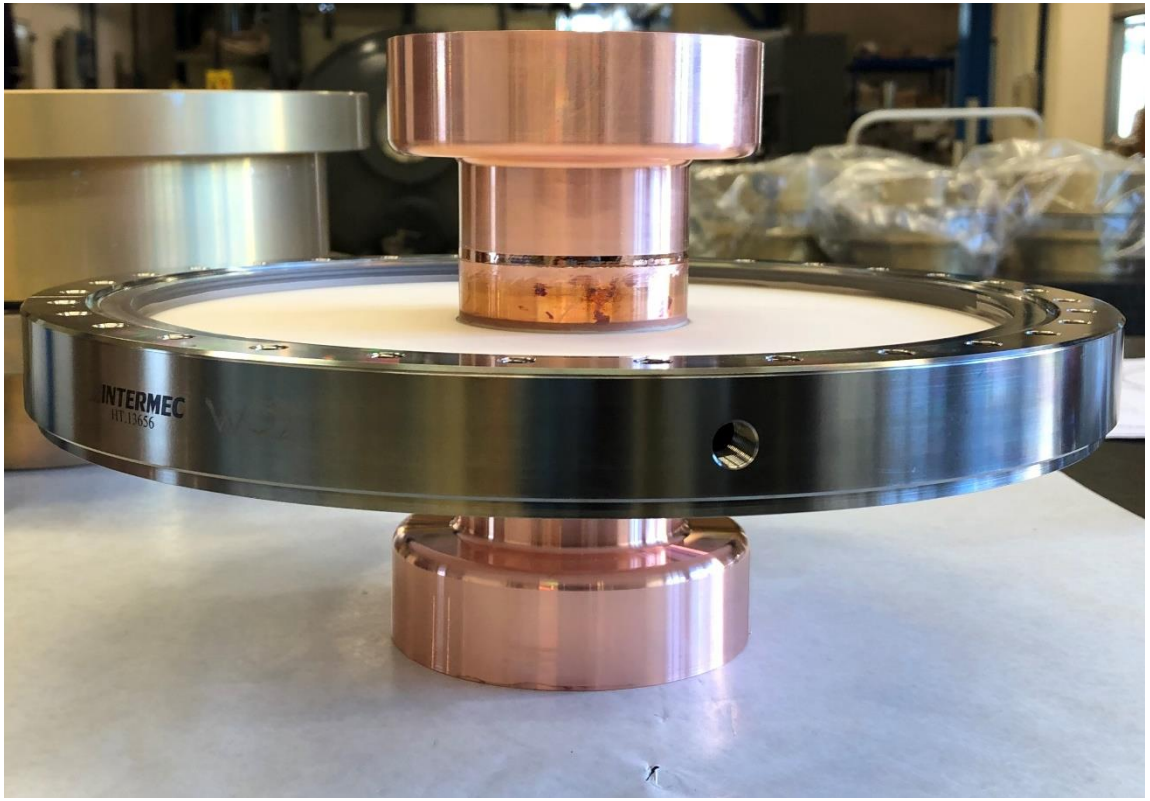
Metal Joining at CERN – The Forming and Welding-Section (EN-MME-FW)



Current Leads for superconducting magnets

Brazing amongst joining processes

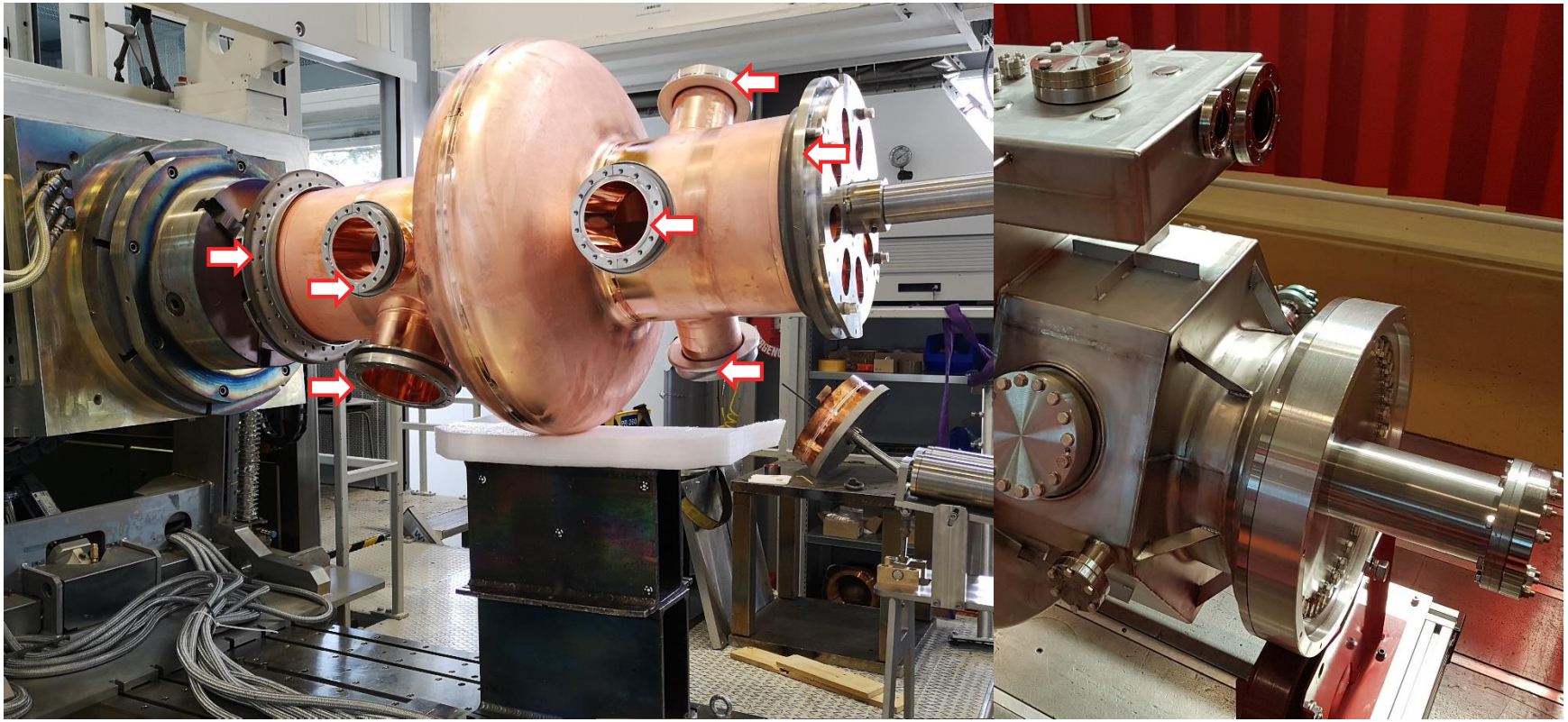
Metal Joining at CERN – The Forming and Welding-Section (EN-MME-FW)



RF-Couplers of SPS-Accelerating Cavities

Brazing amongst joining processes

Metal Joining at CERN – The Forming and Welding-Section (EN-MME-FW)



LHC Accelerating RF-Cavities

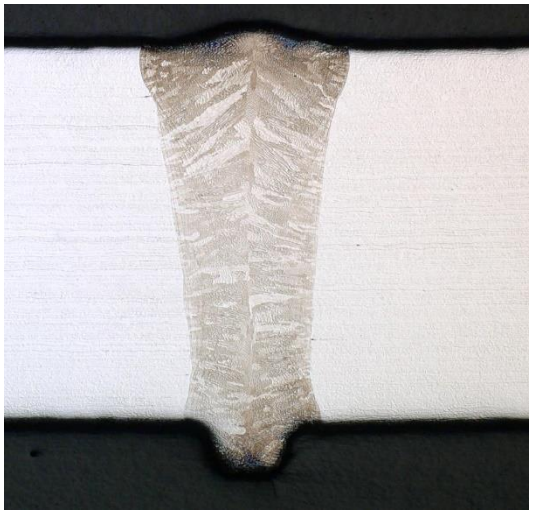
Brazing amongst joining processes

The terms **Brazing** and Soldering contain a group of welding processes, where components are joined by a filler metal whose liquidus temperature is below the solidus/melting temperatures of the components' materials.

Soldering: $\theta_{solidus}$ <450°C

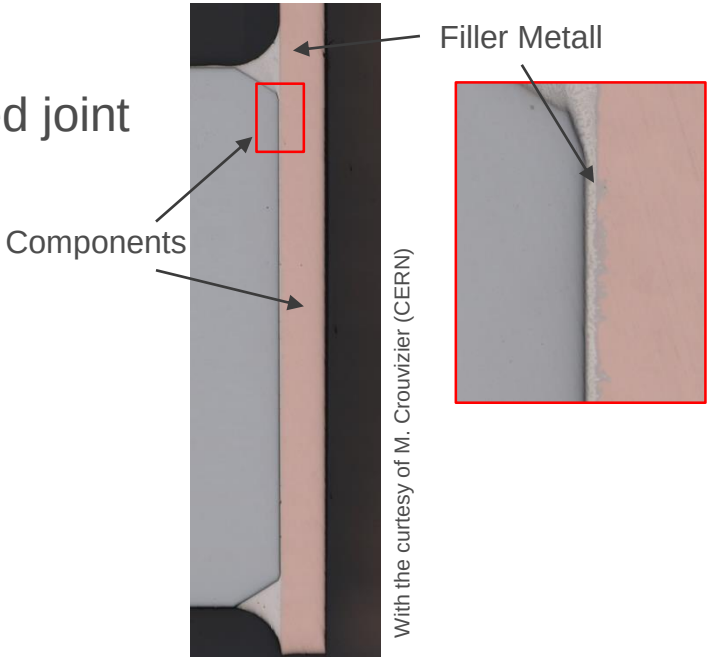
Brazing: $\theta_{solidus}$ >450°C

(Fusion) Welded joint



With the curtesy of T. Demaziere (CERN)

Brazed joint

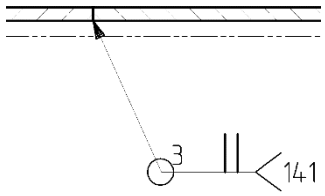


With the curtesy of M. Crouvizier (CERN)

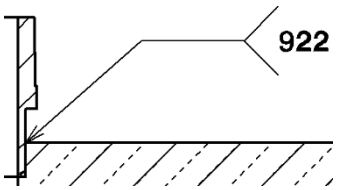
Brazing amongst joining processes

Brazing Processes Classification

(ISO 4063 – "*Welding and allied processes - Nomenclature of processes and reference numbers*")



- **1** Arc Welding
- **2** Resistance Welding
- **3** Gas Welding
- **4** Welding with pressure
- **5** Beam Welding
- **7** Other welding processes
- **8** Cutting and gouging
- **9** Brazing, soldering and braze welding
  - **91** Brazing with local heating
  - **92** Brazing with global heating
    - **921** Furnace brazing
    - **922** **Vacuum brazing**
    - **923** Dip-bath brazing
    - **924** Salt-bath brazing
    - **925** Flux-bath brazing
    - **926** Immersion brazing
  - **93** Other brazing processes
  - **94** Soldering with local heating
  - **95** Soldering with global heating
  - **96** Other soldering processes
  - **97** Weld brazing



Agenda

1. Brazing amongst joining processes
2. Physical principles of (vacuum) brazing
3. Fabrication cycle of vacuum brazed assemblies
4. Equipment and technical requirements
5. CERN-made examples
6. Conclusion

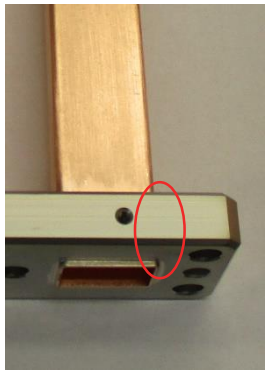
Physical principles of (vacuum) brazing

Objective:

Bonding interfaces of base materials with a filler metal

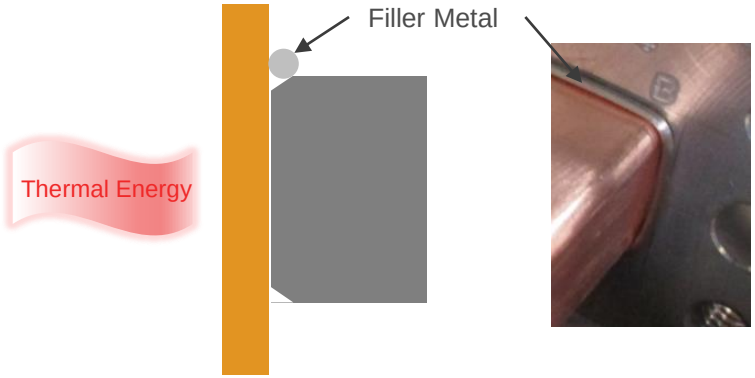
Every brazing process has to go through following steps:

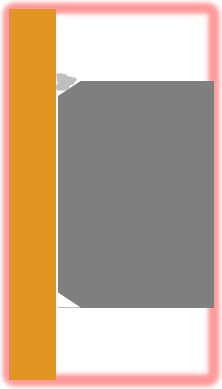
1. Liquification of the filler metal
2. Penetration of the base materials' clearance by the liquid filler metal
3. Creating adhesion between filler and base materials
4. Solification of the filler metal



Physical principles of (vacuum) brazing

1. Liquification of the brazing filler metal (BFM)



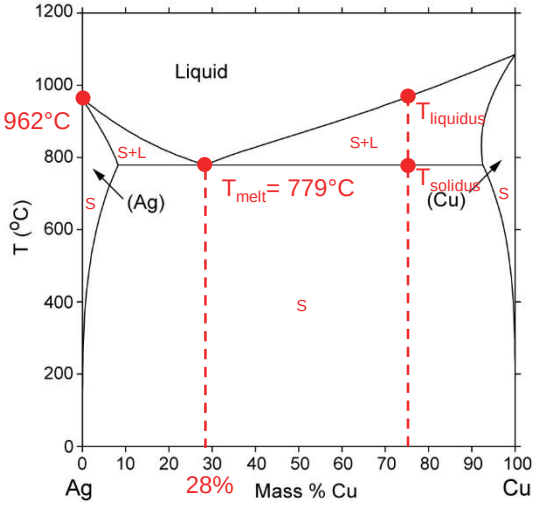


Pure metals:

Concrete melting point (e.g. Silver: 962°C)

Mixture/Alloys (binary, tertiary,…):

- Range of fusion – $T_{solidus}/T_{liquidus}$
- Eutectic reaction – T_{melt}
- (Peritectic systems, intermetallic reactions, …)



Source: www.metallurgy.nist.gov

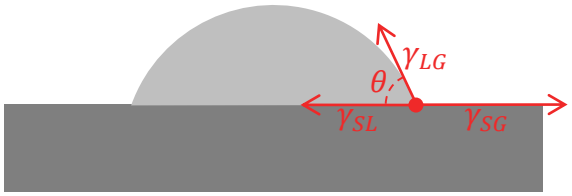
Physical principles of (vacuum) brazing

2. Penetration of the base materials' clearance by the liquid filler metal

Liquid on a solid surface:

Wetting of a solid phase by a liquid defined by surface energies γ

→ Wetting angle



SG: solid-gas; *SL*: solid-liquid; *LG*: liquid-gas

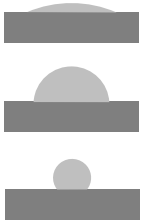
$$\gamma = \frac{\Delta E}{\Delta A}$$

$$\gamma_{SG} - \gamma_{SL} = \gamma_{LG} \cos\theta$$

Θ<<90° → good wetting

Θ=90° → no wetting

Θ>90° → de-wetting



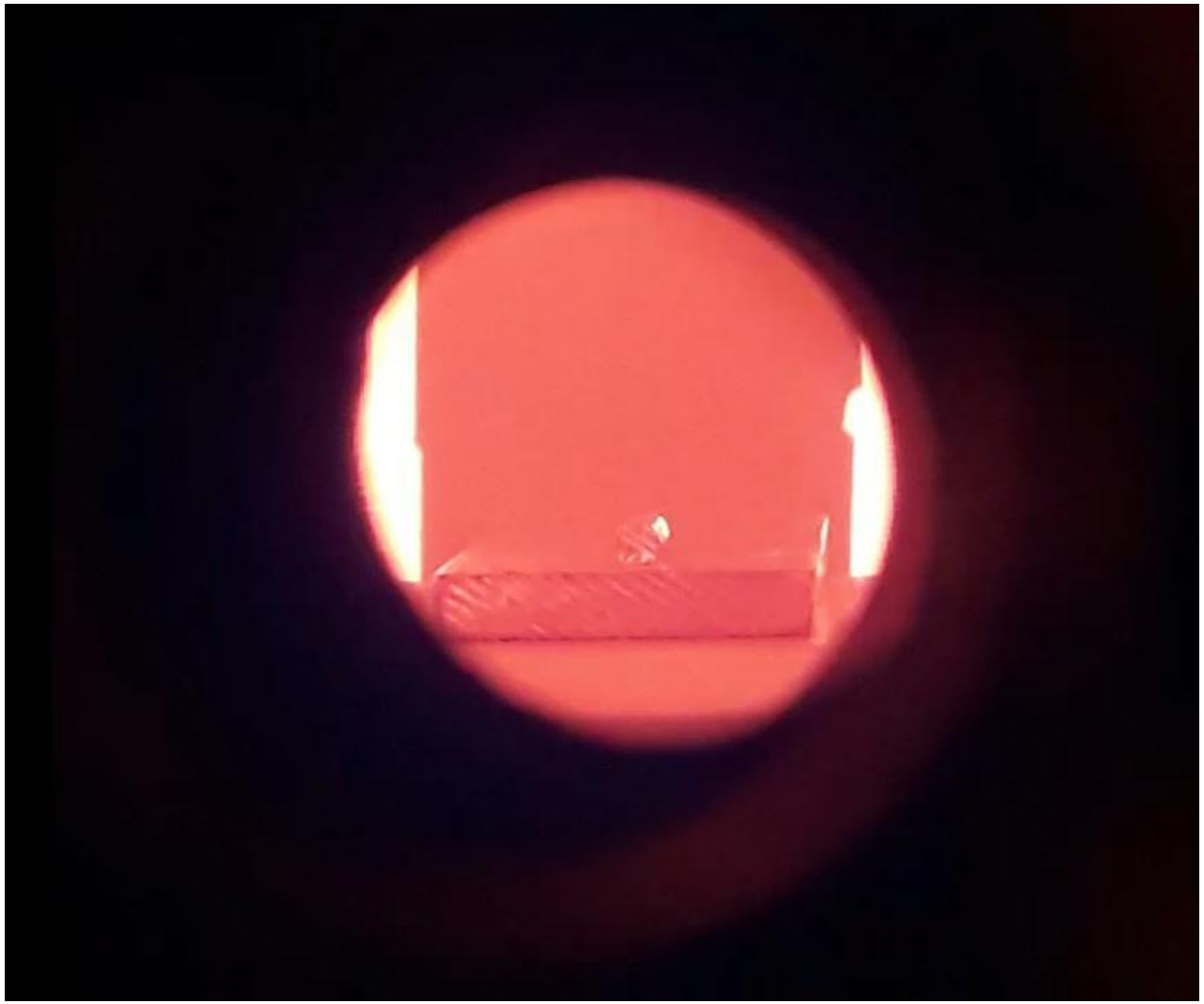
<u>Low wetting angle → good flow on base material</u>

Phase in contact with liquid metal (Solid/Liquid)	Θ
Pure metal (Mo/Cu)	10-30°
Semiconductors (Ge/Si)	≈40°
Carbon (C/Au)	120-135°
Ceramics, e.g. oxides (Al_2O_3/Ag)	120-140°

Source: N. Eustathipoulos et al., *Wettability at High Temperatures*

Problem: Most metals create an oxide-layer on their surface exposed to normal atmosphere, especially at higher temperatures! → <u>metallic surface must be provided</u>

Physical principles of (vacuum) brazing



Physical principles of (vacuum) brazing

2. Penetration of the base materials' clearance by the liquid filler metal

Liquid between solid surfaces:

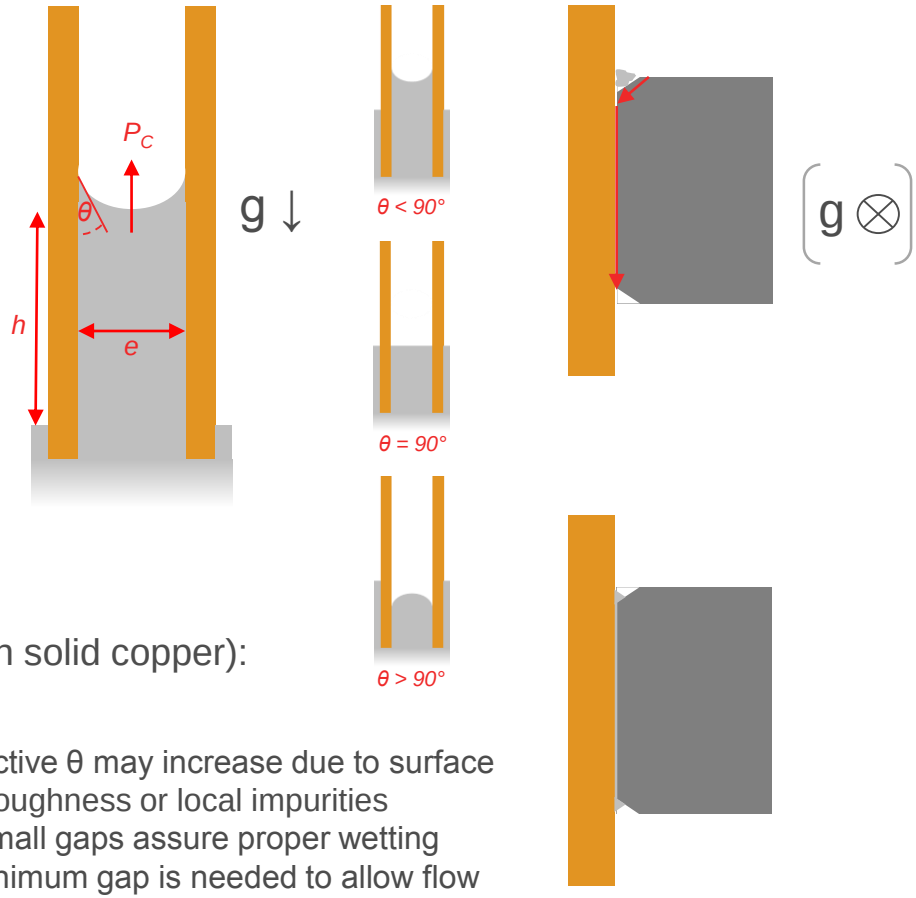
Reduction of surface energy results in force

→ Capillary pressure P_C

$$P_C = \frac{2(\gamma_{SL} - \gamma_{LG})}{e} = \frac{2\gamma_{LG}\cos\theta}{e}$$

$$P_C = g\rho_{BFM}h$$

Equilibrium for non-reactive wetting.



Typical values for molten metalls (e.g. AgCu28 on solid copper):

γ_{LG}≈0.9 J/m^2; ρ=10^4 kg/m^3; θ≈10°

For e=200 µm → h≈0.1 m

For e=30 µm → h≈0.6 m

The effective θ may increase due to surface roughness or local impurities
→ small gaps assure proper wetting
→ a minimum gap is needed to allow flow (defined by filler metals viscosity)

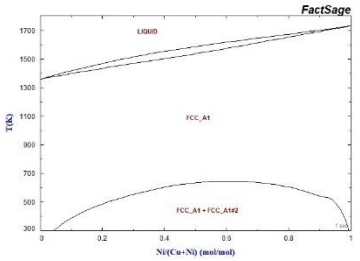
Physical principles of (vacuum) brazing

3. Creating adhesion between filler and base materials

Metallic continuity to assure maximal possible joint strength

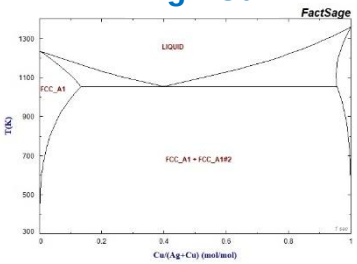
a) Solubility between filler material and base material

Cu - Ni



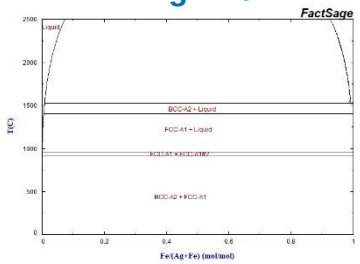
fully soluble

Ag - Cu



partly soluble

Ag - Fe

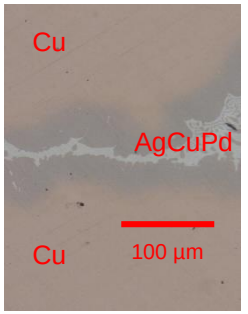


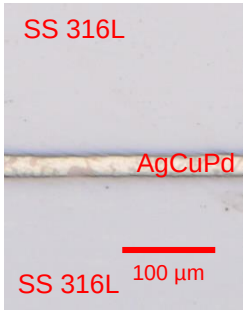
not soluble

Source: http://www.crct.polymtl.ca/fact/

The solubility of the elements present at the provides the possibility that filler and base material can interact and create a “smooth” transition.

Not or poorly soluble metals will result in distinct, separate phases with the phase boundary as joint layer. → weak mechanical strength





Physical principles of (vacuum) brazing

3. **Creating adhesion between filler and base materials**
4. **Solidification of the filler metal**

Metallic continuity to assure maximal possible joint strength

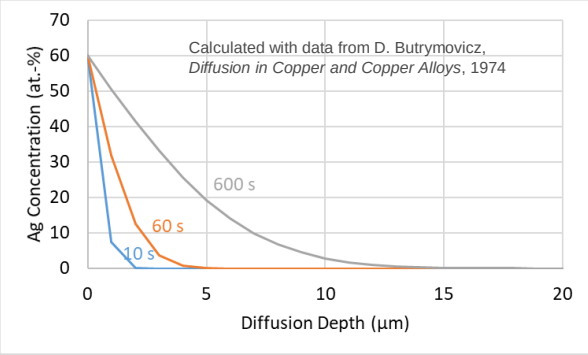
b) Diffusion to create a continuous transition

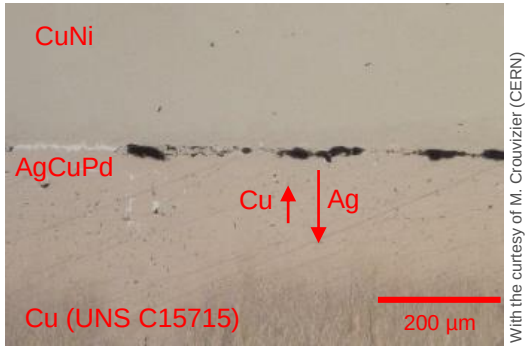
Depending on the filler and base material combination the components exchange material through diffusion.

→ Continuous material transition with no discrete weak interface

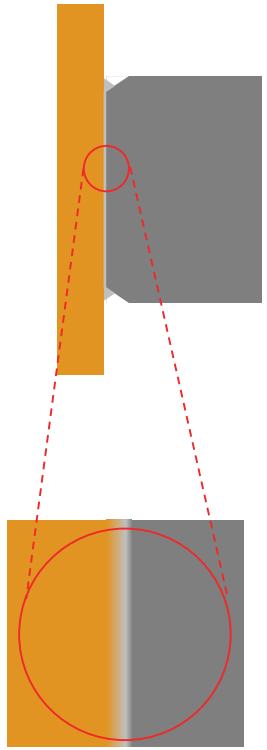
→ Dwell for a certain period in the range of the brazing temperature enhances diffusion and can improve the mechanical strength

Excessive diffusion: Porosity through Kirkendall-effect possible!





With the curtesy of M. Crouvizier (CERN)



Done!

Physical principles of (vacuum) brazing

The principles of a brazing process are clear.

How does it work in real life?

- Heating of the workpiece

  The volume of the brazed interface must be homogenously heated at brazing temperature:

  Local heating: Torch/flame, inductive heating, laser, electron beam

  Global heating: Immersion in molten liquid (salt, filler metal, flux), furnace heating (convection or radiation)

- Wetting of the base material with liquid filler metal

  The filler metal (usually) only wets a metallic surface. Most metals possess an oxidised surface! Heating under exposure of oxygen may furtherly thicken the oxide-layer.

  - Using flux agent to remove oxides by chemical/physical dilution during brazing. Mostly chemical compounds with halogen-atoms (F, Cl)
  - → Commonly used for manual and automatic flame brazing. Parts need to be cleaned thoroughly afterwards as flux residuals are corrosive.

  Brazing under inert or reducing atmosphere can provide a clean, metallic surface for brazing. Interaction of applied gases with materials must be considered.

  Or it is done under vacuum!

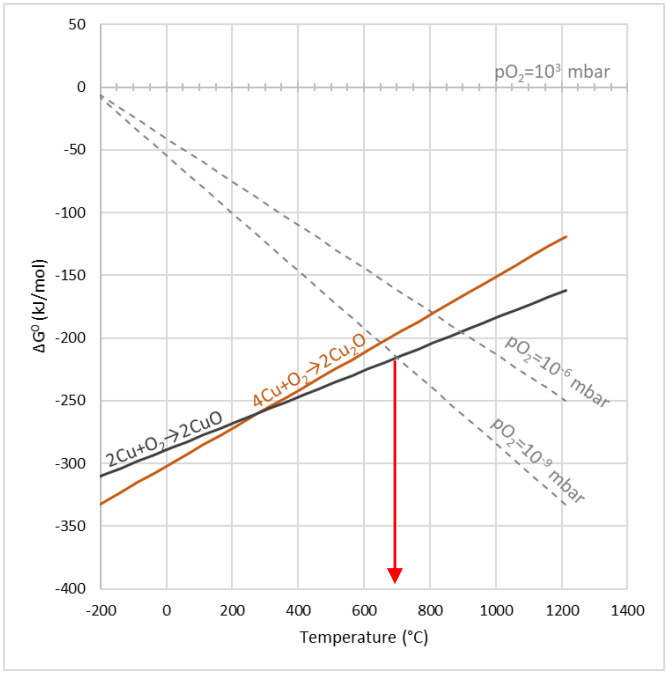
Physical principles of **vacuum** brazing

Heating up metals under vacuum

Residual pressures with high vacuum systems in the range of 10^{-6} mbar → 10^{-9} (1 ppb) of atmosphere

No further oxidation during heating/brazing cycle!

Thermodynamic stability of metal oxides:



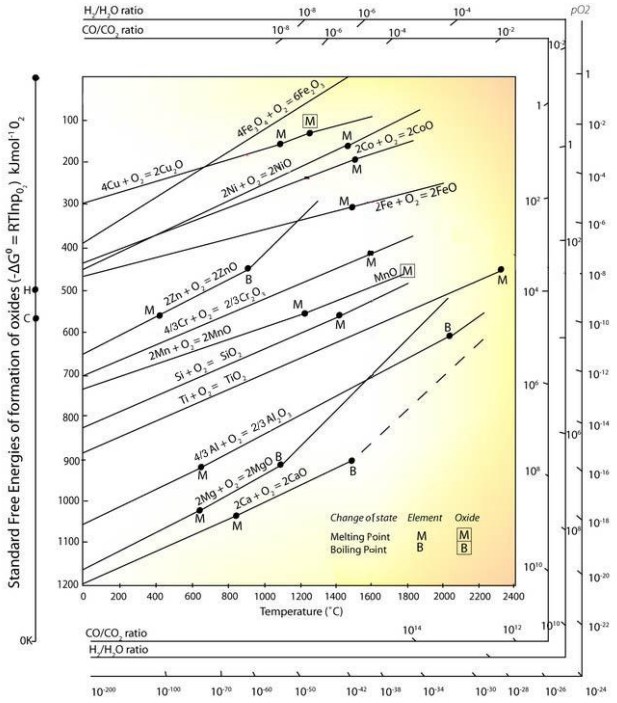
$$\frac{2x}{y}M + O_2 \underset{\Delta G}{\rightarrow} \frac{2}{y}M_xO_y$$

$$\Delta G = \Delta H - T\Delta S$$

Eq.: $\Delta G - RT\ln\left({}^{p_{O_2}}/_{p_0}\right) = 0$

Oxides of e.g. Cu, Fe, Ni can be reduced at brazing temperatures >700°C and HV-conditions!*

*kinetics not taken into account



Source: University of Cambridge ((www.doitpoms.ac.uk)

Physical principles of **vacuum** brazing

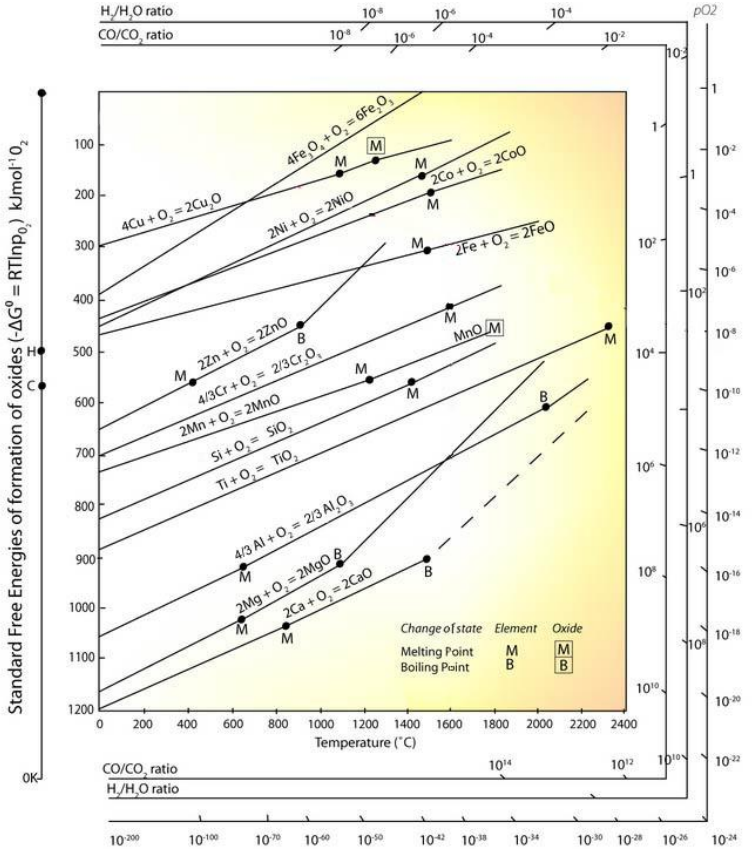
Main considerations of vacuum Brazing

Metals with an initially thin oxide scale (prepared by mechanical/chemical cleaning) can be wetted under vacuum through

- mechanical expulsion by wetting/capillary force
- thermodynamic reduction through high *T* and low p_{O2}

The stability of formed oxides on metallic surfaces defines in first line the brazeability under vacuum:

Brazeability	Nature of Oxide	Example
good/excellent	Low enthalpy, less stable at HT	Ag, Cu, Ni
fair/difficult	Stable, slowly forming/thin scale	Cr, Nb, Ti
Very difficult	Stable, fast forming/thick scale	Al, Mg, Be



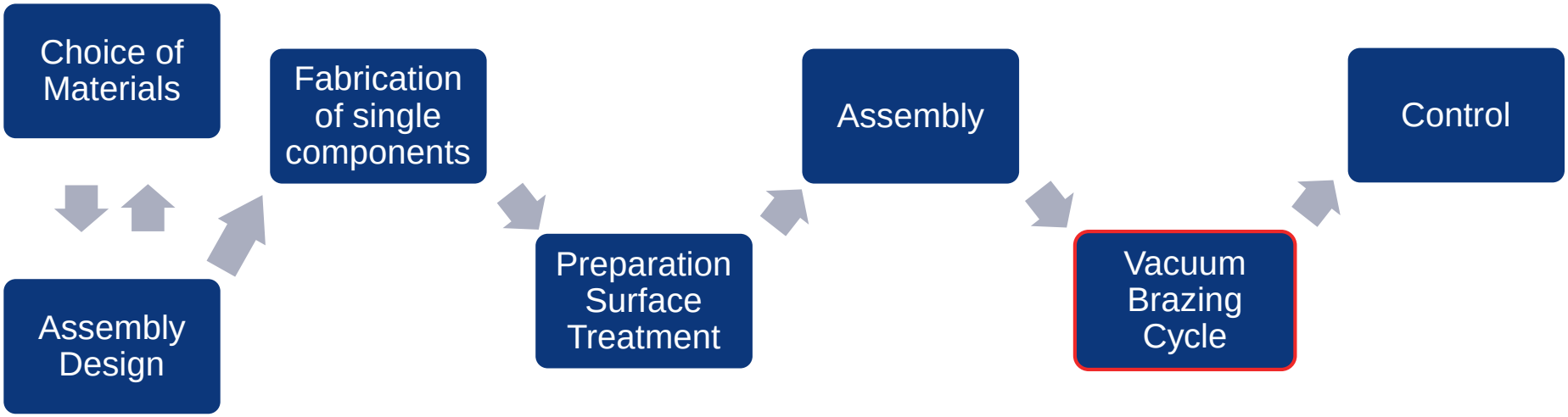
Source: University of Cambridge ((www.doitpoms.ac.uk)

Agenda

1. Brazing amongst joining processes
2. Physical principles of (vacuum) brazing
3. Fabrication cycle of vacuum brazed assemblies
4. Equipment and technical requirements
5. CERN-made examples
6. Conclusion

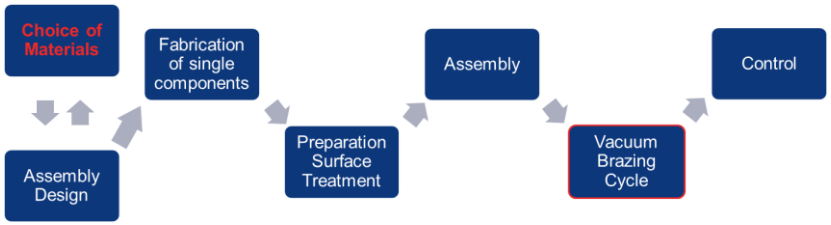
Fabrication cycle of vacuum brazed assemblies

Steps to assemblies joined by vacuum brazing

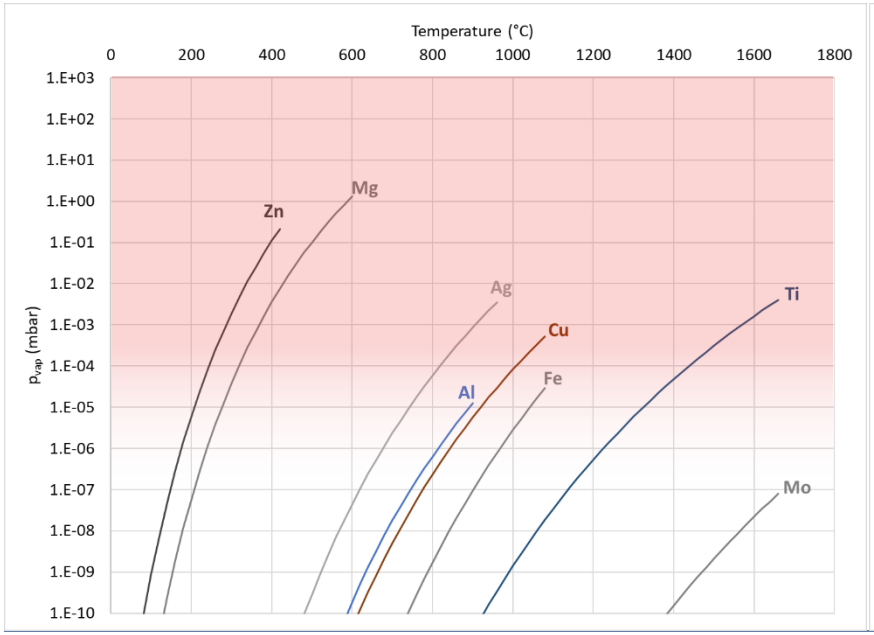


Fabrication cycle of vacuum brazed assemblies

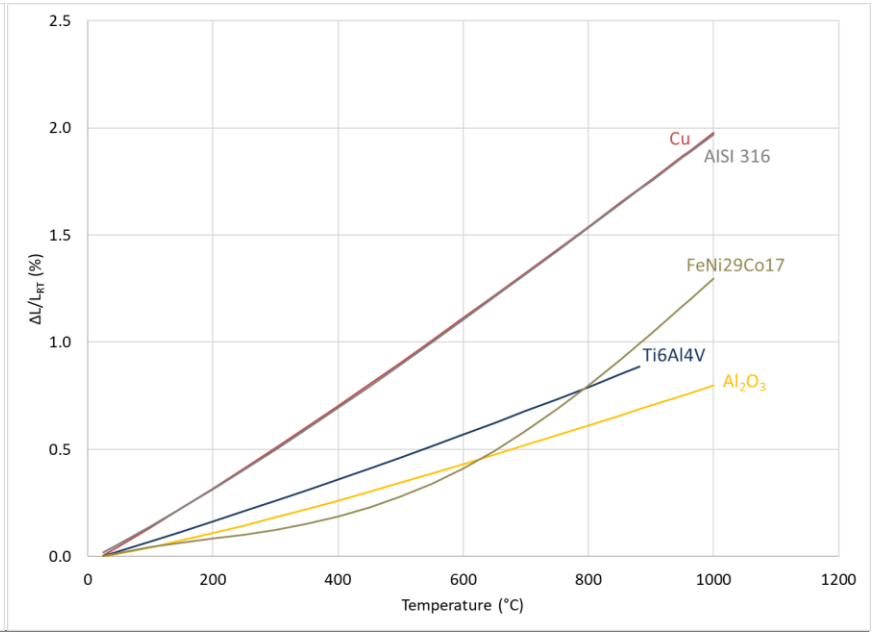
Compatibility with vacuum brazing process



- Brazeability of metallic surface
- Compatibility with vacuum heat treatment to brazing temperatures – Vapour pressure, **annealing**
- Mismatch of coefficient of thermal expansion for different materials – Brazing gap, residual stress



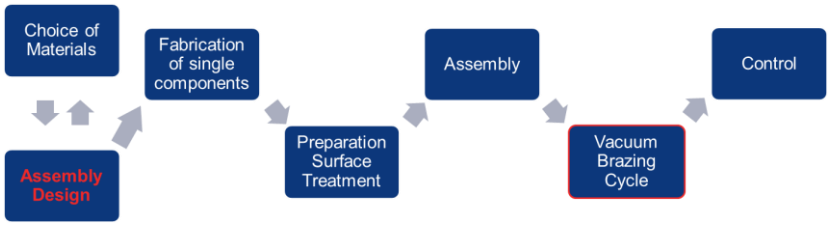
Calculated from CRC Handbook of Chemistry and Physics



With the curtesy of S. Mathot (CERN)

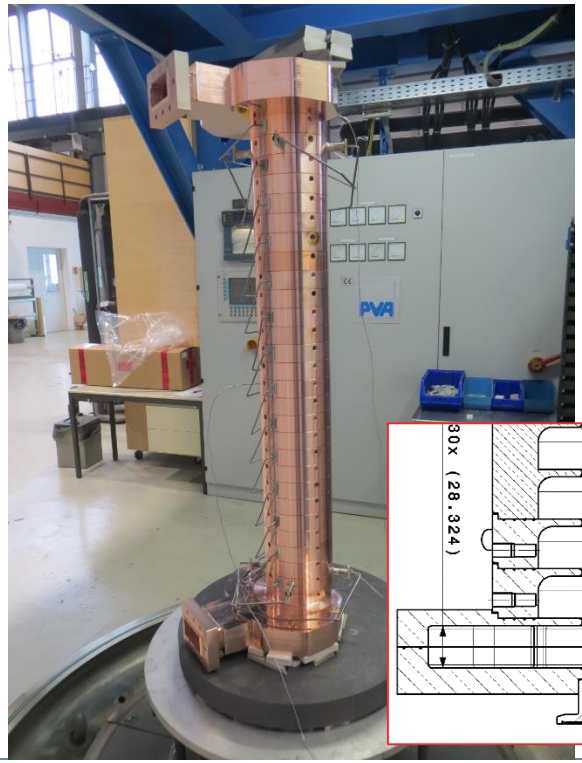
Fabrication cycle of vacuum brazed assemblies

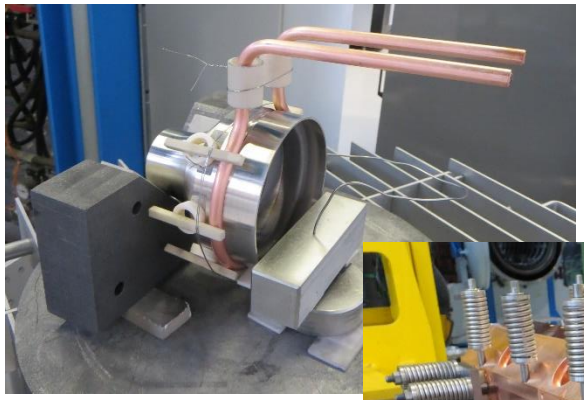
Allowing correct assembly and proper brazing gaps

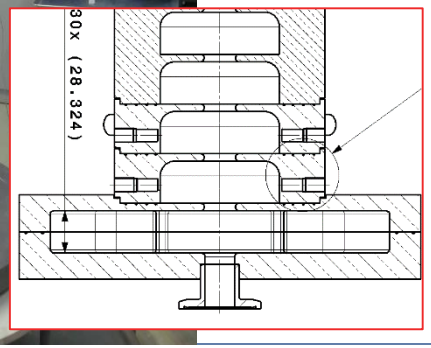


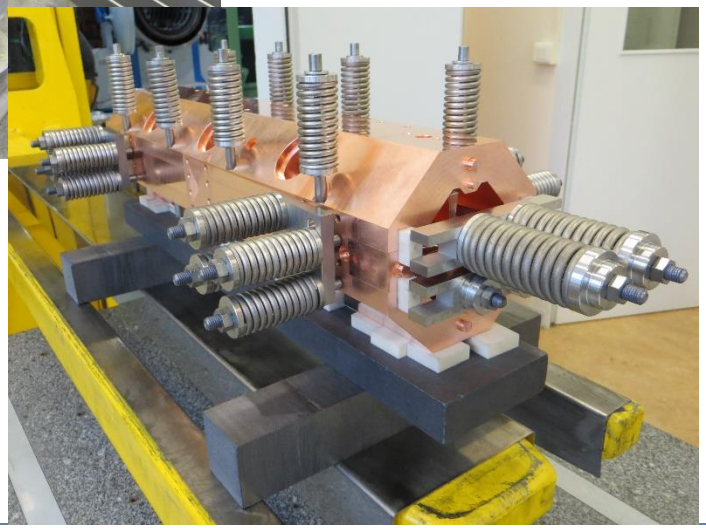
- Vacuum brazing executed in a furnace chamber:

  Stable assembly configurations
  → Positioning and loading of assemblies
  → Alignment features









Fabrication cycle of vacuum brazed assemblies

Allowing correct assembly and proper brazing gaps

- Vacuum brazing executed in a furnace chamber

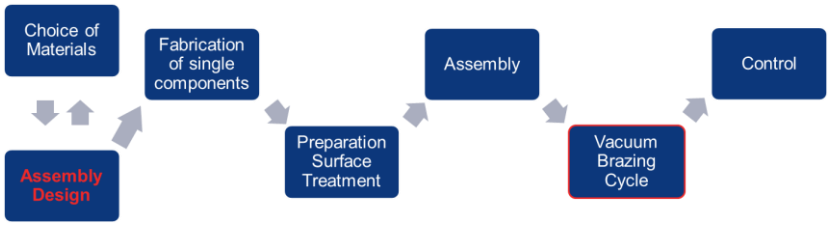
  Stable assembly configurations

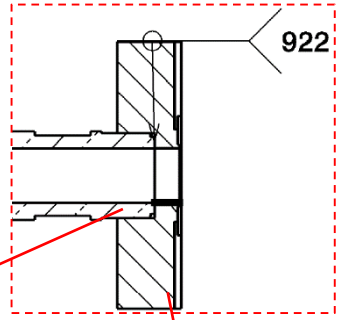
- Design features to assure gaps/capillary joints

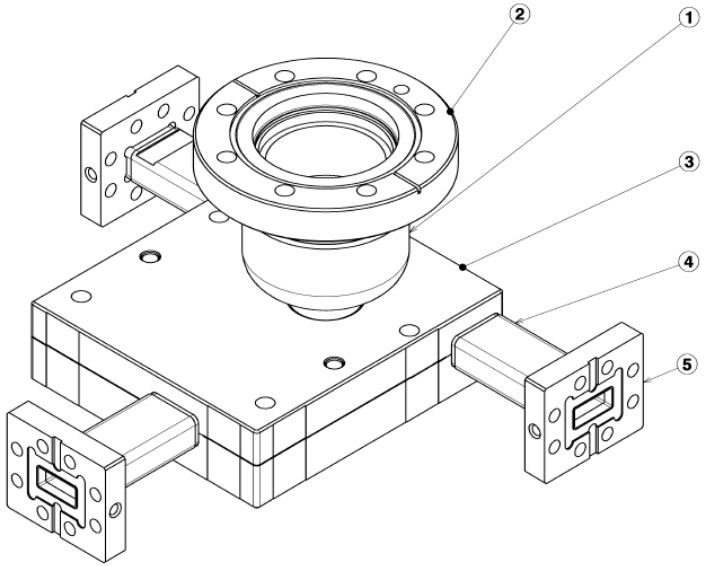
  Tolerances, surface roughness

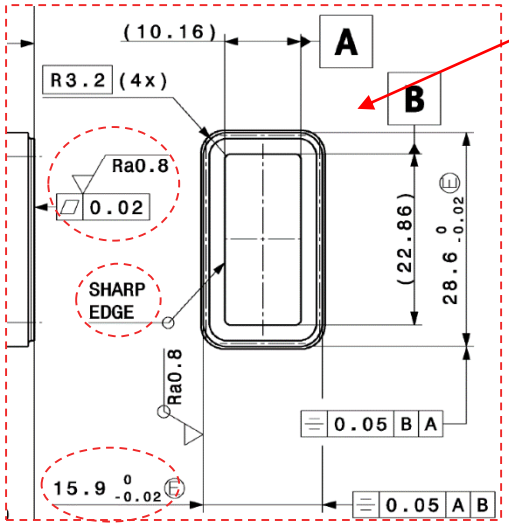
- Placement of filler metal

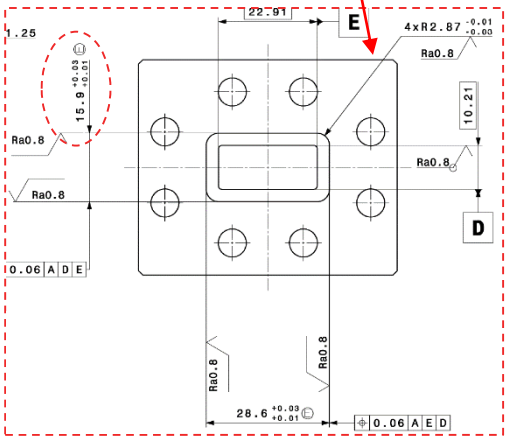
  Wires, foils, paste





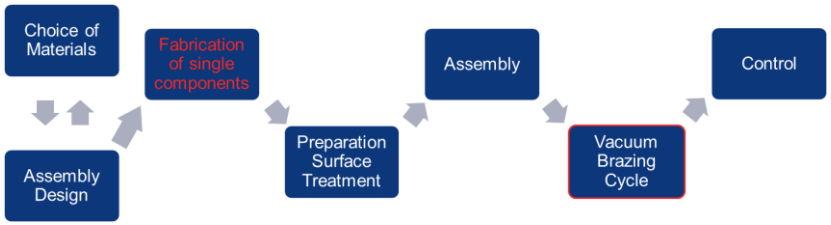






Fabrication cycle of vacuum brazed assemblies

Fabrication of correct pieces



- Sourcing of raw material – Identification, certification

- Residual stresses – raw state, cold working during machining process

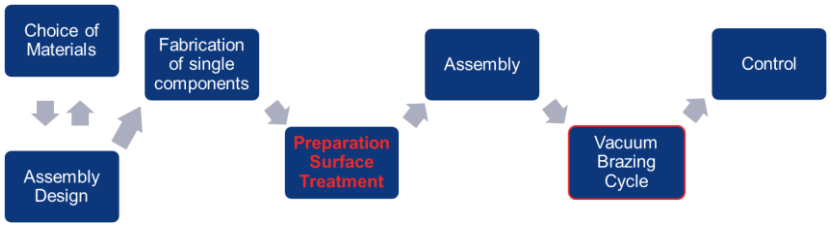
  As the brazing cycle represents a heat treatment, stress relief can cause undesired deformations

  → Intermediate heat treatments for vacuum brazed components often required

Stress relief of copper under air (200-250 °C)

Stress relief of spin-formed FeNiCo-parts under vacuum (850°C)

Fabrication cycle of vacuum brazed assemblies



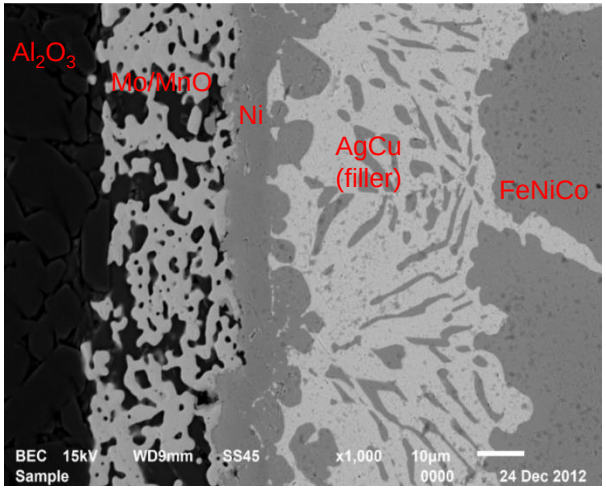
Important step: The right surface treatment

- Degreasing/cleaning of all surface contaminants (oil and other hydrocarbons)
- Pickling to remove oxide scale and keep oxidation as little as possible
- Plating of certain surfaces to improve/enable wetting during brazing

  Ni-layer on (stainless) steels

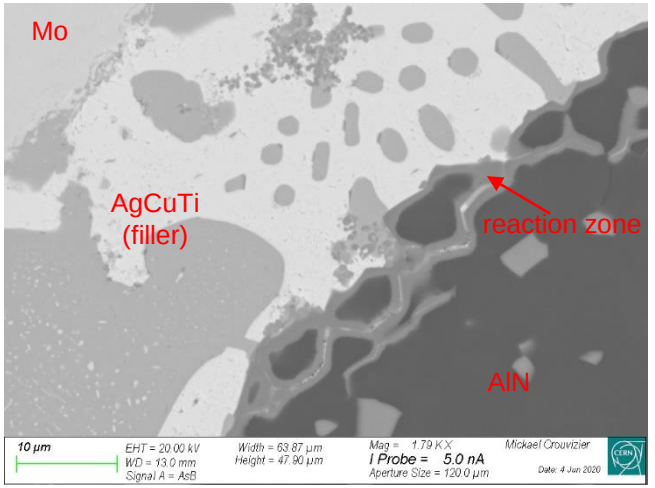
  Metallisation layers on non-metallic/ceramic materials allow joining by brazing

Metallised alumina (Mo/Mn+Ni)



Source: Yanf Lei, Process of research on the alumina ceramics metallization, IEEE 2015

SEM-micrograph of brazed alumina with Mo/Mn-metallisation



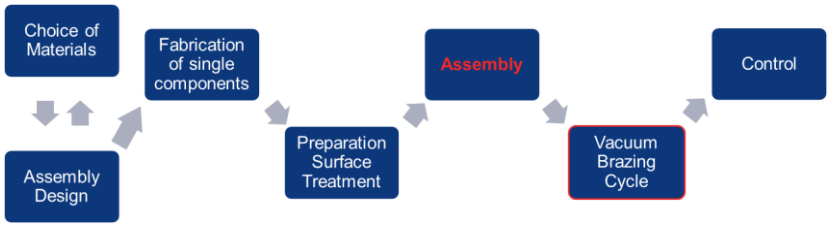
With the curtesy of M. Mayer (CERN)

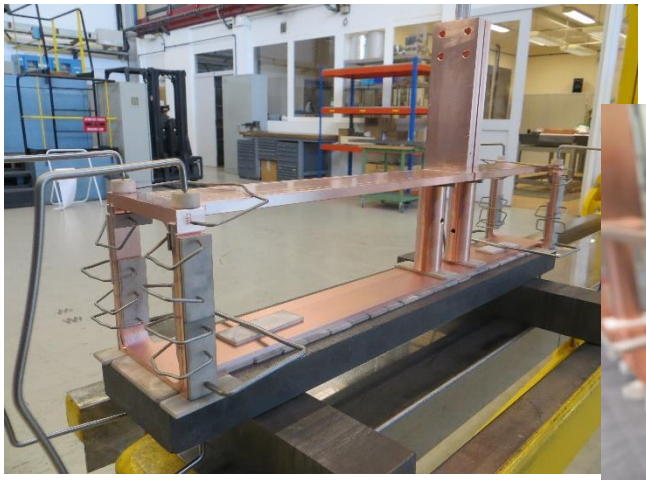
SEM-micrograph of brazed AlN with active filler metal

Fabrication cycle of vacuum brazed assemblies

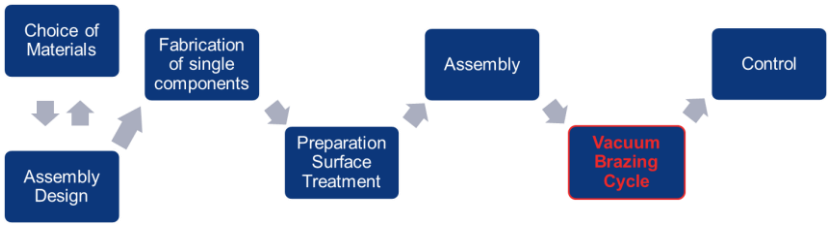
Adequate assembly for furnace

- Alignment and charging of brazed interfaces maintained through the whole brazing process
- Stable placement of filler metal (wires, foils, powder/paste)
- Support structures and tooling must be compatible with heat treatment and thermal expansion of part



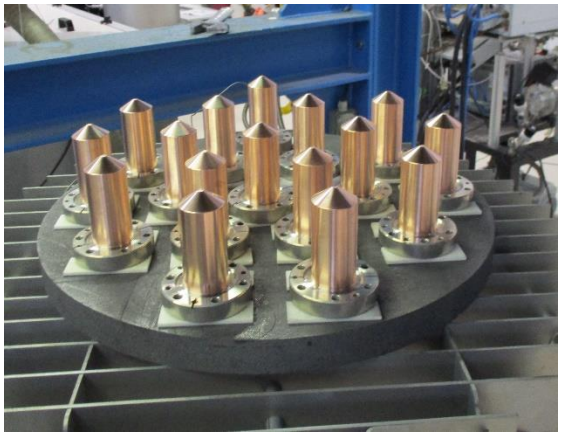


Fabrication cycle of vacuum brazed assemblies



The actual brazing happens

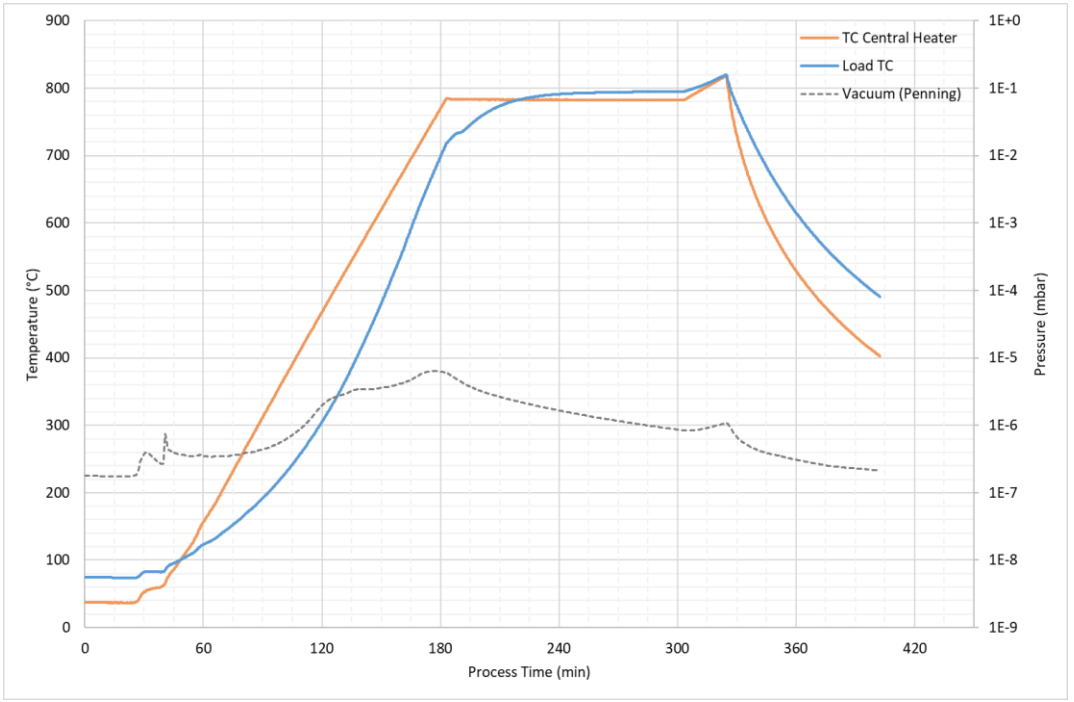
- Pump-down of vacuum furnace to HV (<10^{-5} mbar)
- Heating cycle varies with filler metal, thermal inertia and diffusivity of load, material requirements
- Usual cycle duration including cooling >12 h



Stainless steel-copper assembly with Ag86.5Cu26.5Pd5 (ISO 17672-Pd 287)

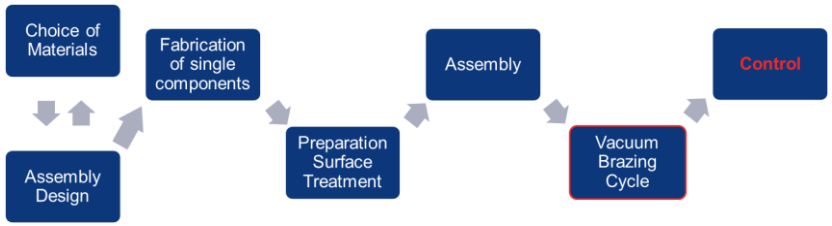
$T_{solidus} \approx 810°C$

Load thermocouple inserted in one of the flanges

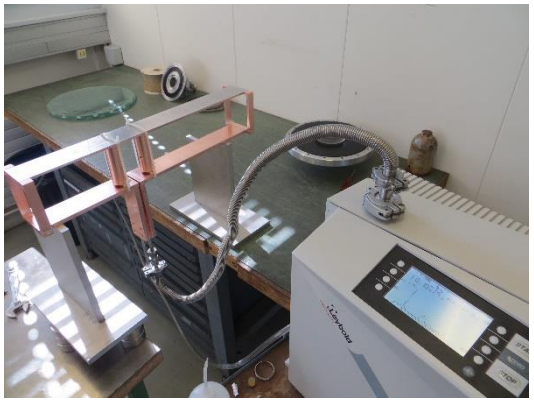


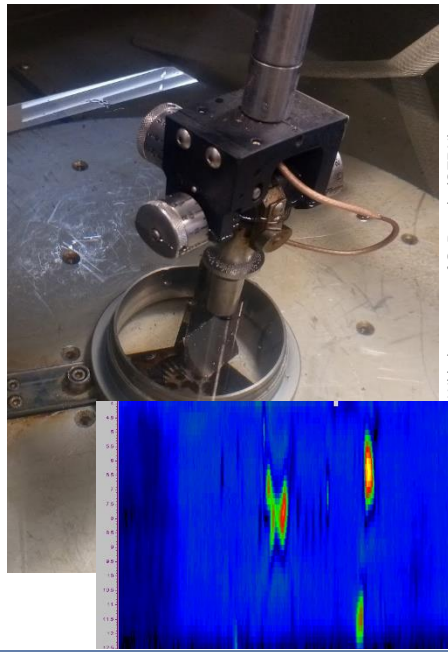
Fabrication cycle of vacuum brazed assemblies

Control of brazed assemblies
according to requirements
(e.g. qualification according to EN 13134/ISO 13585)

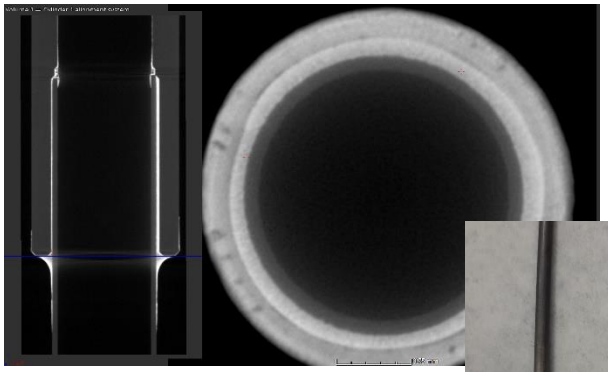


- Visual control
- Leak tests
- Metrology
- Destructive Testing: Mechanical Testing, Metallographic Cut
- Non Destructive Testing: **Ultrasound Inspection**; X-Ray/µCT for small assemblies (material/spacial resolution)





With the curtesy of S. Bonnin (CERN)



With the curtesy of M. Jedrychowski (CERN)

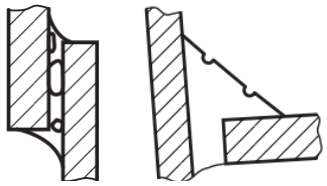
Fabrication cycle of vacuum brazed assemblies

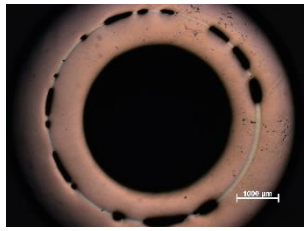
… and what can go wrong:

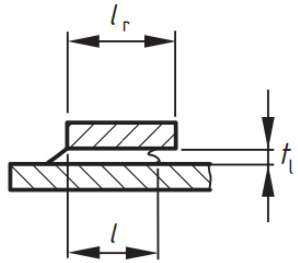
Most appearing defects of vacuum brazed joints

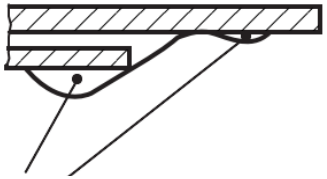
- Cavities/pores
- Lack of penetration
- Excess of filler metal
- Erosion/alloying by filler metal

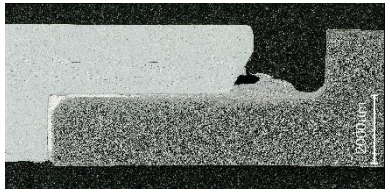
Micrograpahs with the curtesy of M. Meyer, M. Crouvizier and A. Gallifa Terricabras (CERN)

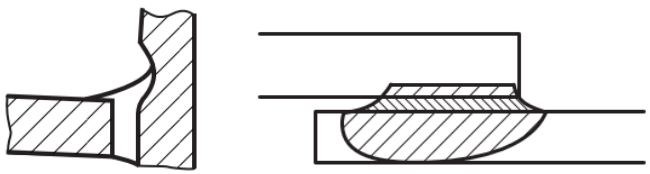


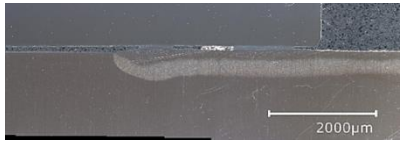












Illustrations from EN ISO 18279:2003

Agenda

1. Brazing amongst joining processes
2. Physical principles of (vacuum) brazing
3. Fabrication cycle of vacuum brazed assemblies
4. Equipment and technical requirements
5. CERN-made examples
6. Conclusion

Equipment and technical requirements

Vacuum Furnace Chamber

Heating source:

- **Resistors**
- Induction
- (Infrared)

$$\frac{dQ_{net}}{dt} \approx \epsilon_1 \sigma \left(\boldsymbol{T_2}^4 - \boldsymbol{T_1}^4 \right)$$

Hot zone/resistors made from refractory metals mainly

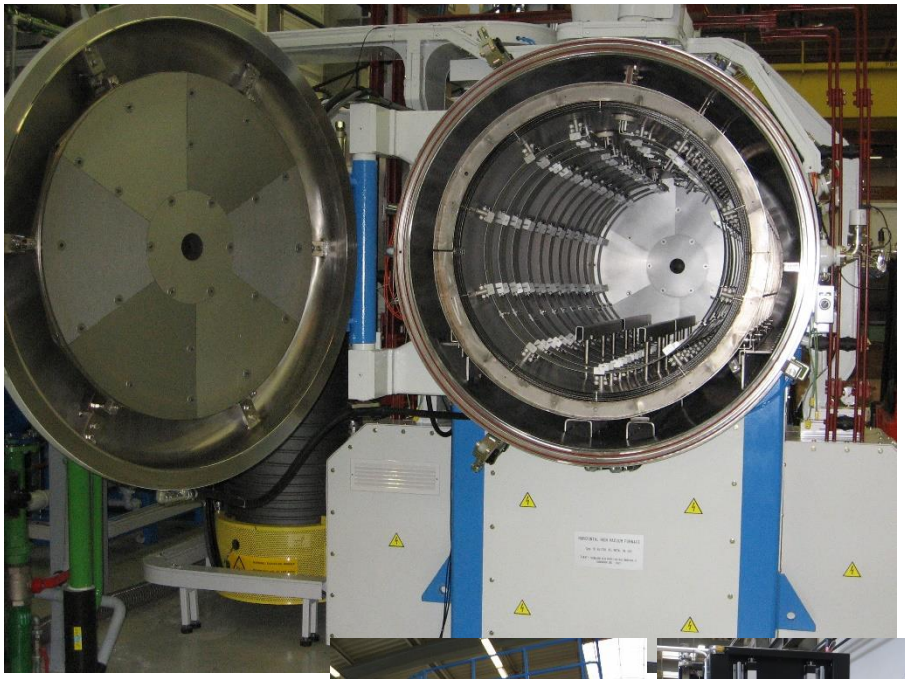
Insulation by thermal screens

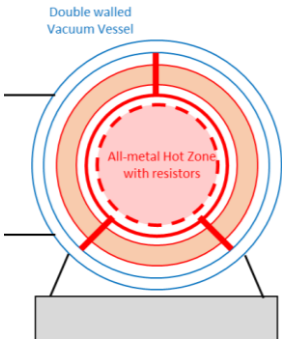
Water-cooled vessels

T_{max} (Mo-hot zone): 1300-1600°C

Power rating (hot zone ≈ 700 l): 200 kW

Usual temperature uniformity ±5-10°C (>600°C)





Equipment and technical requirements

Vacuum Group

Pumping Group

Primary/Foreline:

Mechanical Pumps (rotary vane/roots booster)

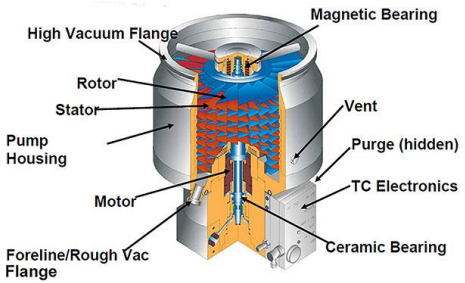
→ 10^{-3} mbar

High Vacuum Pump:

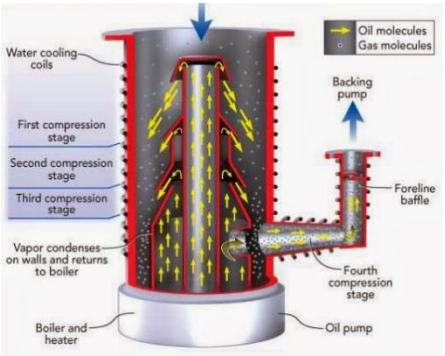
Oil-Diffusion ($p_{min} \approx 10^{-7}$ mbar), $S_{pump} \uparrow$

Turbomolecular ($p_{min} \approx 10^{-9}$ mbar), $S_{pump} \rightarrow$

Cryopump ($p_{min} \approx 10^{-9}$ mbar), $S_{pump} \uparrow \uparrow$



Source: www.lesker.com



Source: upervacindustries.blogspot.com

Equipment and technical requirements

Vacuum Group

Generation of Vacuum

Vacuum Leak tightness: 10^{-6}…10^{-3} mbar/(l×s)

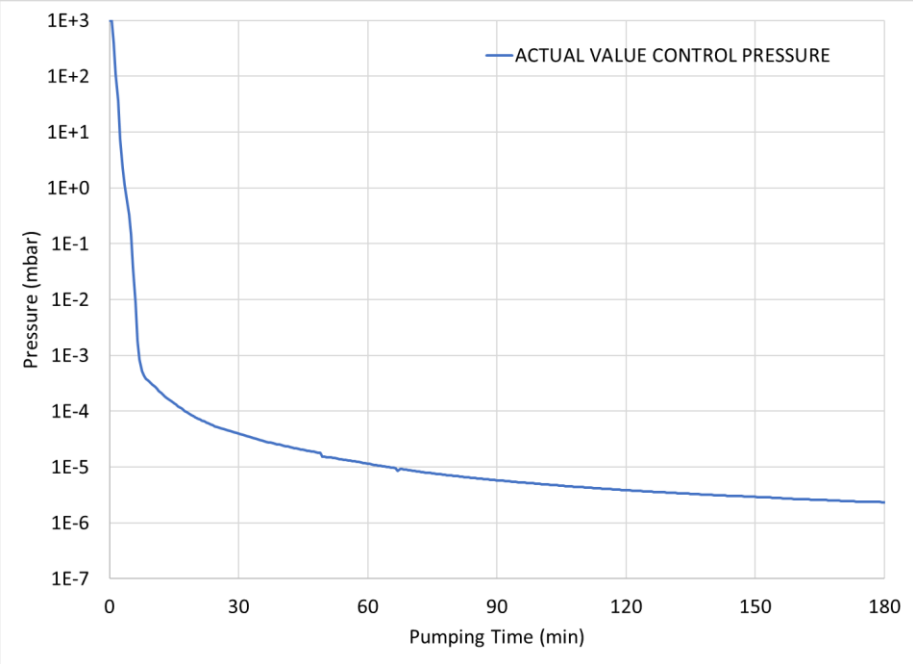
$$p_{t\to\infty} = \frac{Q_{leak}}{S_{pump}}$$

Cleanliness (hydrocarbons, volatile elements)

Compression rates for molecular pumps:

$N_2/O_2/Ar$	$\approx 10^8$
He	$\approx 5\times10^5$
H_2	$\approx 5\times10^4$

→ predominantely H2 present in residual gas



Equipment and technical requirements

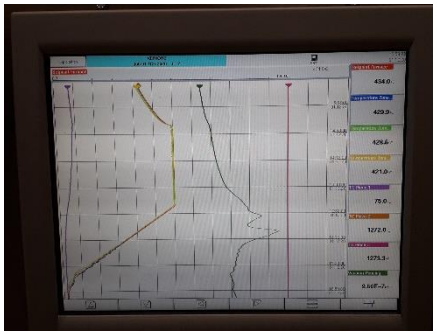
Control and Automation

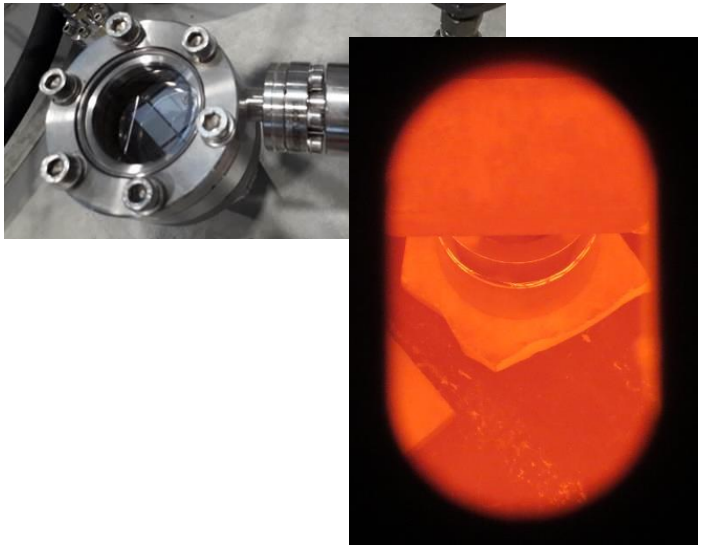
Automation per PLC

Pumping sequence, Heating cycle…

Recording of process parameters

Pressure readings, furnace-/pump-/load-temperatures





Brazing surveillance

Load thermocouples, furnace windows (>700°C)

Agenda

1. Brazing amongst joining processes
2. Physical principles of (vacuum) brazing
3. Fabrication cycle of vacuum brazed assemblies
4. Equipment and technical requirements
5. CERN-made examples
6. Conclusion

CERN-made examples

Joining of dissimilar materials

Stainless steel – Copper

Transitions from ss-flanges to copper for vacuum chamber, RF-cavities,…

Septum coils for kicker magnets. Stainless steel-capillaries brazed into conductor

Usual filler metals:

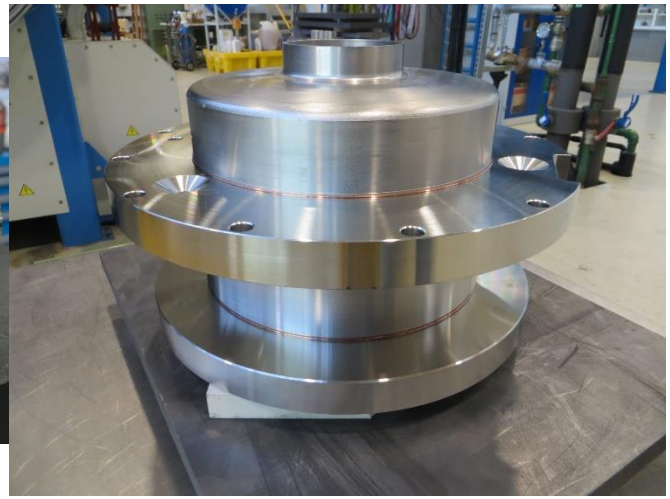
- Ag72/Cu28 (eutectic, T_{braze}: 780°C)
- Ag68/Cu27/Pd5 (T_{braze}: ca. 815°C)
- Ag58/Cu32/Pd10 (T_{braze}: ca. 855°C)…

CERN-made examples

Joining of dissimilar materials

Stainless steel – Niobium

Transitions from ss-flanges to Nb for Superconducting RF-cavities,…



Lower membrane of QPR-Cavity

Joining of two materials with a significant mismatch in CTE! (AISI 316 ≈18×10^{-6} K^{-1}; Nb ≈5×10^{-6} K^{-1})

Procedure established by CERN around 30 years ago.

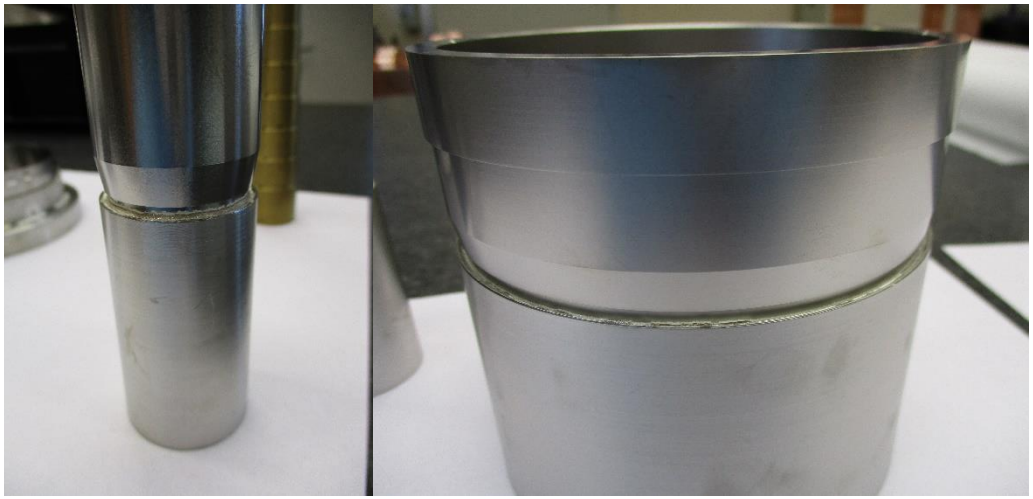
Filler metal:

- Pure Cu (UNS C10100), T_{melt}: 1084°C

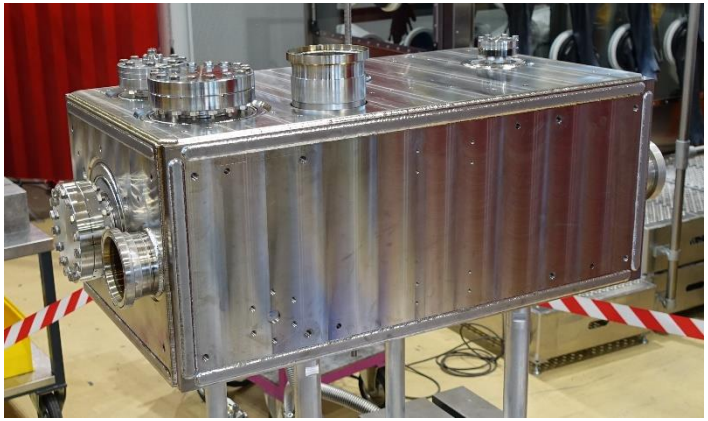
CERN-made examples

Joining of dissimilar materials

Stainless steel – Titanium



Transitions from ss-tubes to Ti (cp) for
He-tank of SRF-cavities



Joining of two materials with mismatch in CTE! (AISI 316 ≈18×10^{-6} K^{-1}; Ti ≈9×10^{-6} K^{-1})

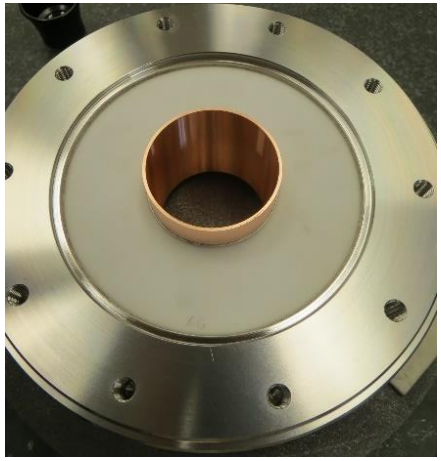
Filler metal:

- Ag88Pd9Ga9, T_{liq}: 880°C – Contains no copper that would form very brittle Ti_xCu_y-intermetallics

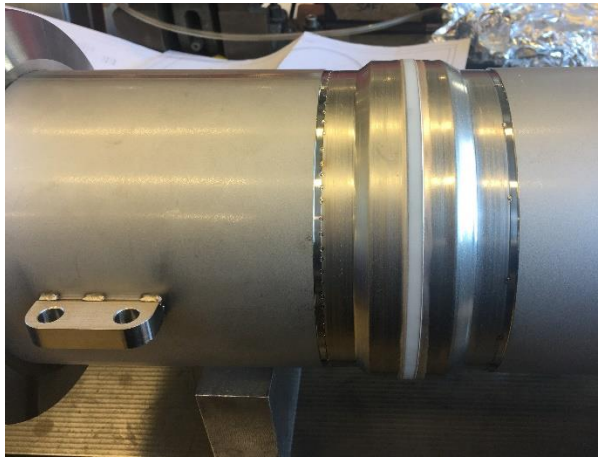
CERN-made examples

Joining of dissimilar materials

Metal – Ceramic Transitions



RF-window for CRAB SRF-Cavity
Ti/Al_2O_3/Cu



Insulator in chamber for BCT
FeNiCo/Al_2O_3

Active Brazing of
FeNiCo to AlN

Metals providing low CTE-mismatch with respect to corresponding ceramic (FeNiCo, Ti, Mo, Nb…)

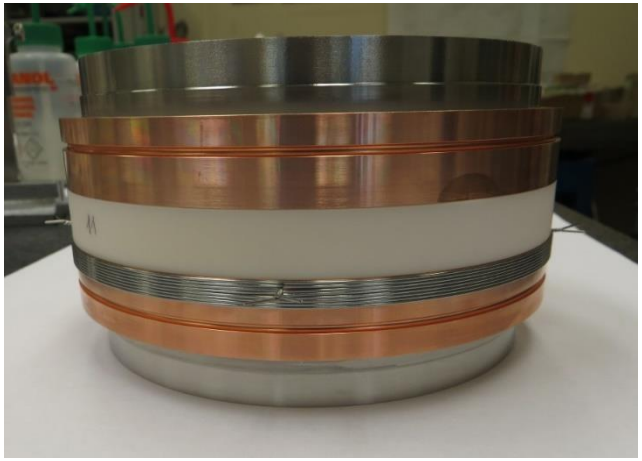
Filler metal:

- Ag72/Cu28 and derivates, T_{braze}: 780-850°C (for metallised ceramics)
- Active Brazing with active brazing filler metals, e.g. Ag63Cu35.25Ti1.75

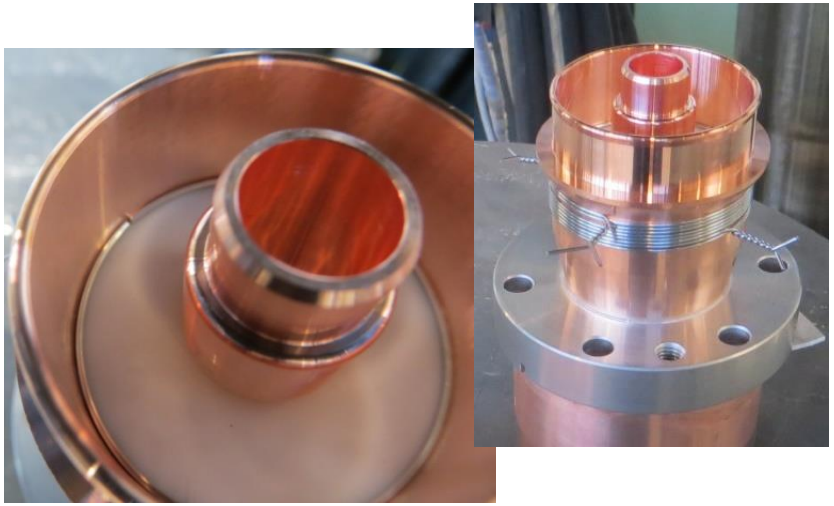
CERN-made examples

Joining of dissimilar materials

Metal – Ceramic Transitions



Non-ferromagnetic BCT-insulator
Al_2O_3/Cu/316L

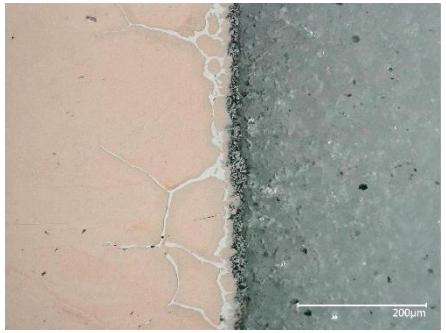


RF-feedthrough for HOM-couplers
Cu/Al_2O_3/Cu/316L

Although high mismatch in CTE, Cu/Al_2O_3-transitions feasible thanks to low yielding of copper

Filler metal:

- Metallised ceramic with additional Ag-plating creates in-situ a eutectic reaction (Liquid Transfer Brazing)

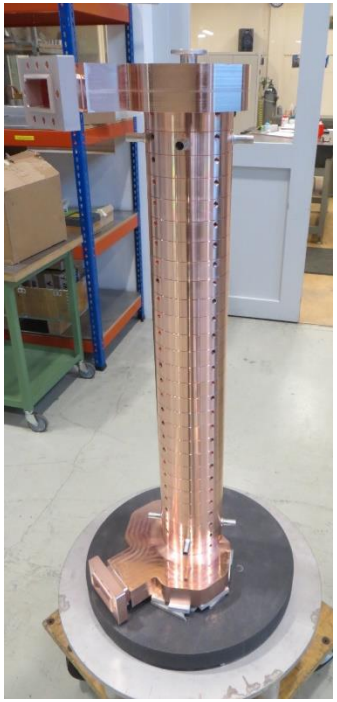


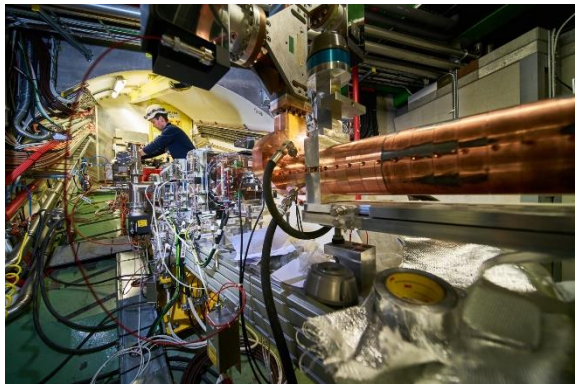
With the curtesy of M. Crouvizier (CERN)

CERN-made examples

Assembly of RF-Cavities

RFQ for Linac4





Structure for e-acceleration for AWAKE

Precise assemblies – require often various machining and heat treatment steps

Accuracy of assembly <20 µm over large dimensions

Agenda

1. Brazing amongst joining processes
2. Physical principles of (vacuum) brazing
3. Fabrication cycle of vacuum brazed assemblies
4. Equipment and technical requirements
5. CERN-made examples
6. Conclusion

Conclusions

When we use brazing – especially under vacuum?

- Joining of dissimilar materials
  - Different metalls with problematic metallurgic reactions during welding
  - Metal to ceramic-joints
- Joining of materials that are not possible or difficult to weld
  - Copper and its alloys (high thermal conductivity, welding commonly performed, but delicate)
  - High melting refractory materials (high energy input, practically only welded by laser or electron beam)
  - Non-metallic materials (e.g. ceramics, carbon)
- Avoiding of welding shrinkage/fusion of base materials
  - Assemblies with tight tolerances
- Joints not accesible for welding
  - Assemblies with large areas to be joined
  - Complex joint geometries
  - Hidden joints

Conclusions

Some final words

- An evaluation of which joining/brazing process is the most adequate is important – one vacuum brazing cycle can cost more than 1000 €
- Vacuum brazing is favorable for: Clean/UHV-components, large joint surfaces, precise assemblies of high quality, readily oxidizing/active base materials (Ti, Nb,…)
- The base materials can affect the joint design and the joint design can affect the base material (to be used)
- For a successful assembly, the brazing operator(s) should be involved from the design process on
- Each assembly needs specific process parameters/heating cycles
- Automated process: High reproducibility possible
- Taking all the steps into account, in will take days, or even weeks until an assembly is done by vacuum brazing – please be patient ☺☺☺

Thank you for your attention!

Thanks again for your attention!

CERN | EN ENGINEERING DEPARTMENT