Manufacturing & Assembly for Vacuum Technology

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(For the EN/MME group)

Outline:

Manufacturing

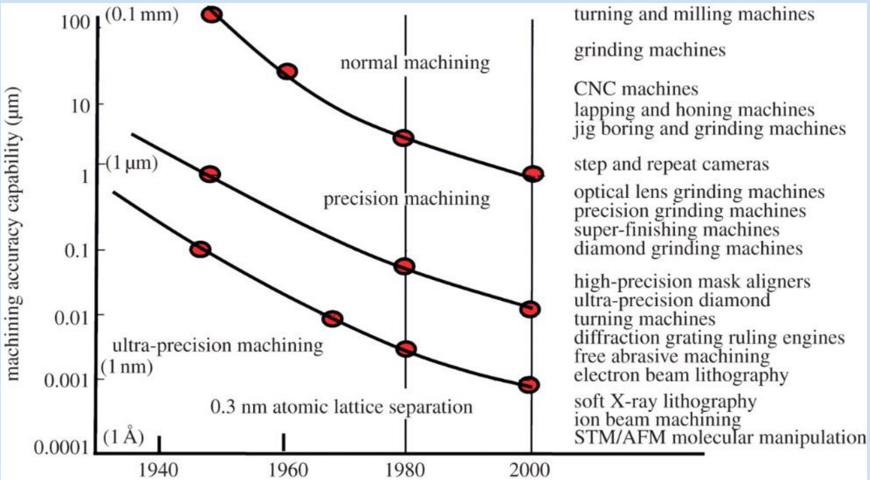
- Introduction
- Precision turning
- Precision milling
- Affected layer
- Diamond tools ultraprecision
- Milling (Machine) center
- Ceramic machining
- Cutting fluids
- Avoided or less appropriate techniques
- Sheet metal forming

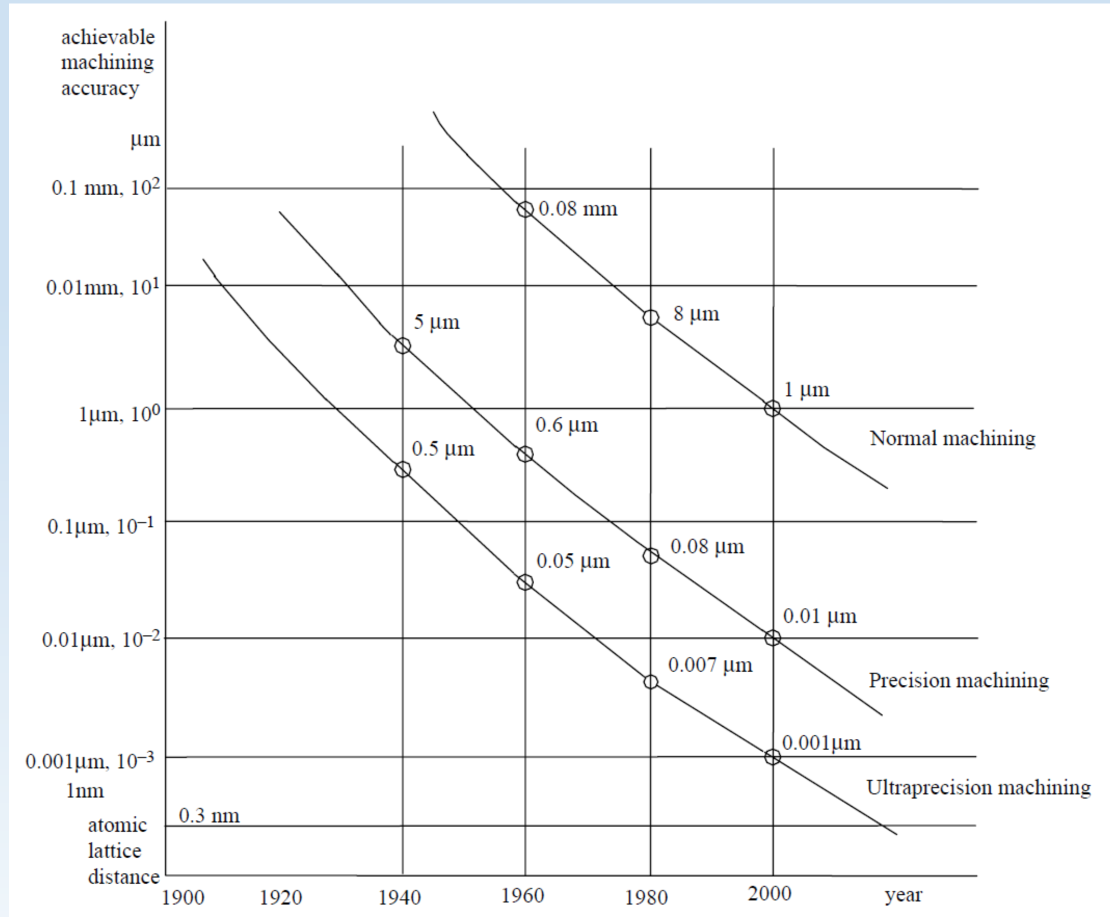
Assembly

- TIG welding
- MIG welding
- Electron and Laser welding
- Welding defects
- Brazing & Soldering
- Vacuum brazing
- Ceramic / metal vacuum brazing
- Vacuum soldering
- Diffusion brazing & Diffusion bonding

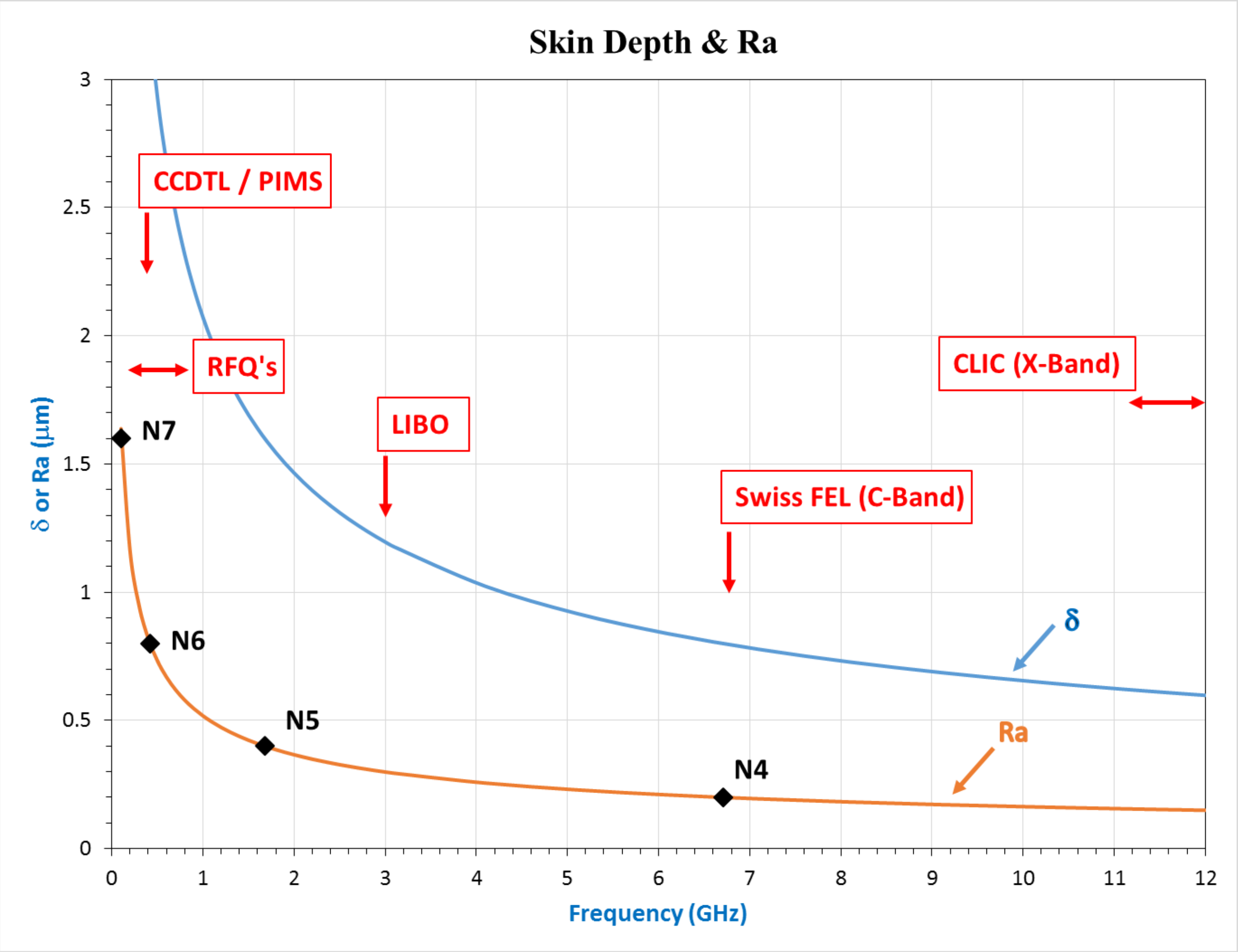
Present trends and future perspectives

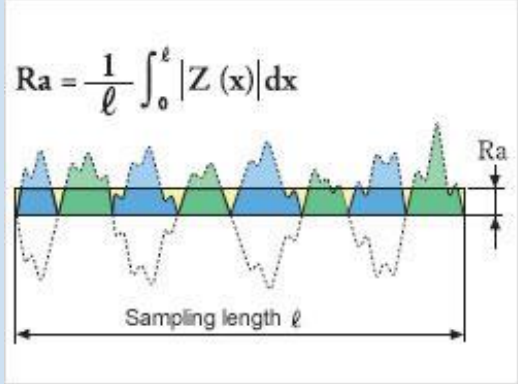
Final remarks - comments





◦ An interpretation of the Taniguchi curves, made in 1983, depicting the general improvement of machine accuracy capability with time during much of the twentieth century.

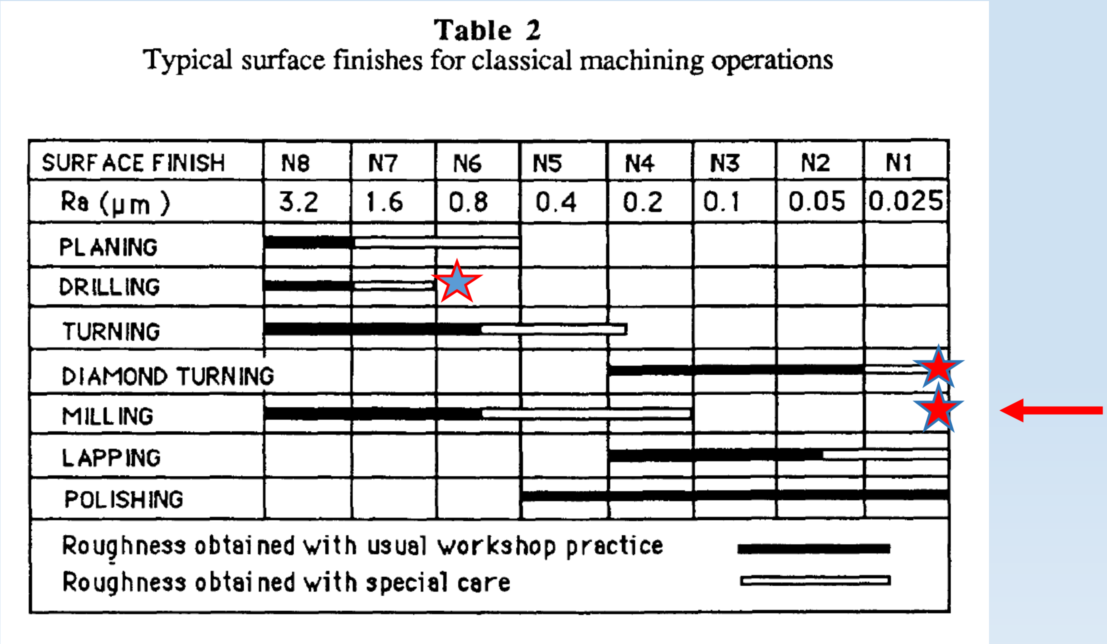




$$\delta = \sqrt{\frac{1}{\pi \mu_0 f \sigma}}$$

(For copper: σ = 5.7 MS/m)

$$Ra \approx \frac{1}{4}\,\delta$$

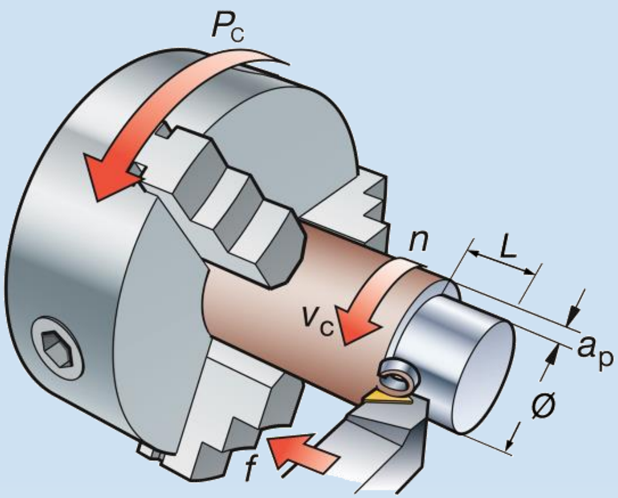


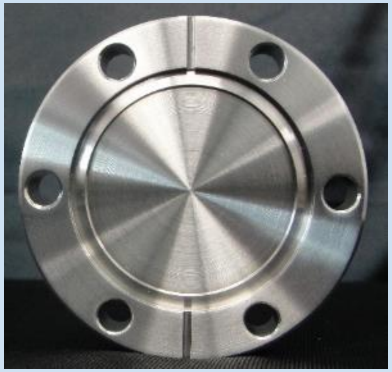
I. Wilson – CAS - 1991

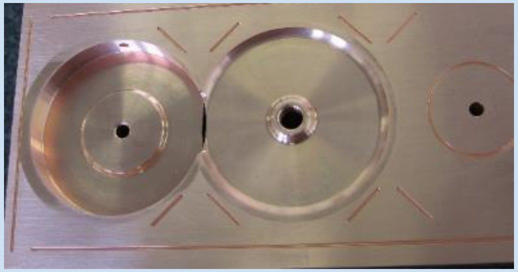
★ S. Garg, *et al* - 2015

★ S. Atieh *et al* - 2011

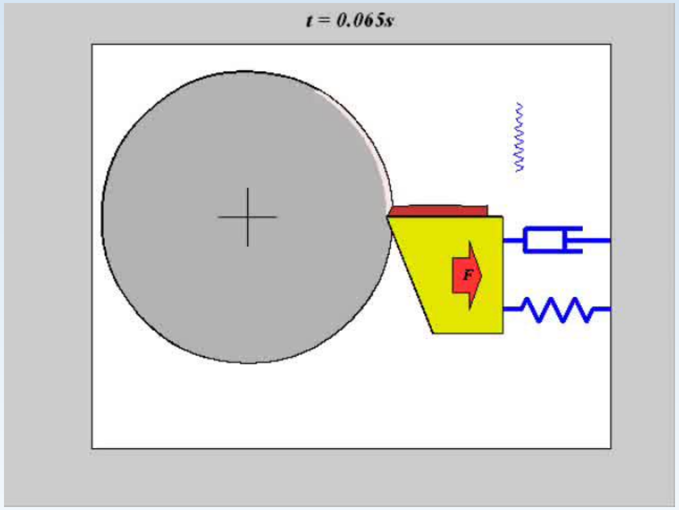
Manufacturing – Precision turning



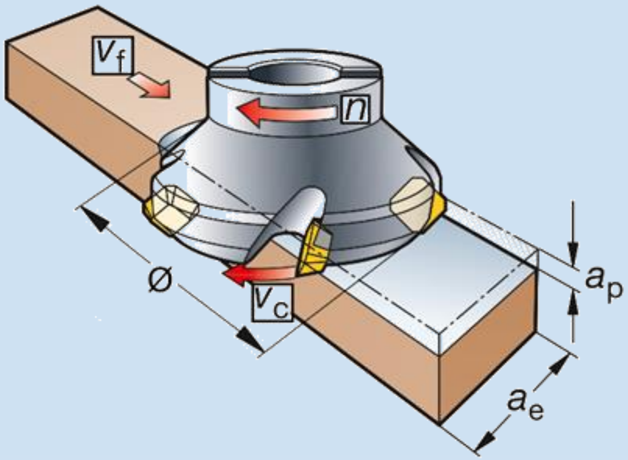




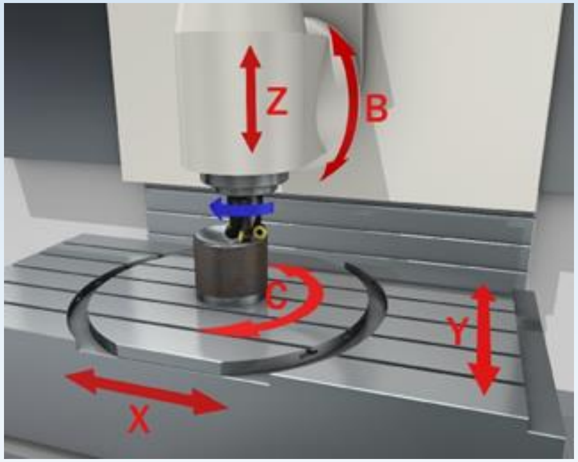
- For axial-symmetry part
- Continuous process (single edge remove all the material)
  - Chip control for process reliability and workpiece quality
  - Chatter ➔ geometry + surface quality control
- Achievable performance on state-of-the-art equipment
  - Shape accuracy ➔ 10 µm
  - Roughness < Ra 0.2 µm (OFE Cu)

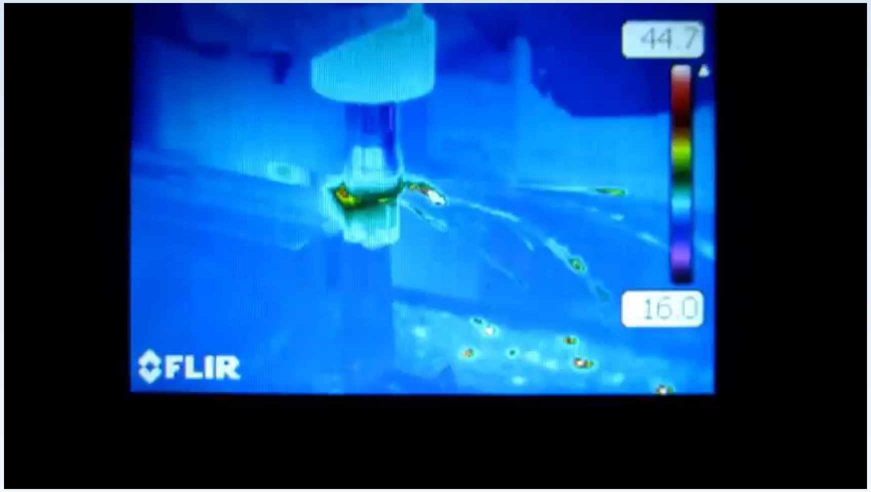


Manufacturing – Precision milling

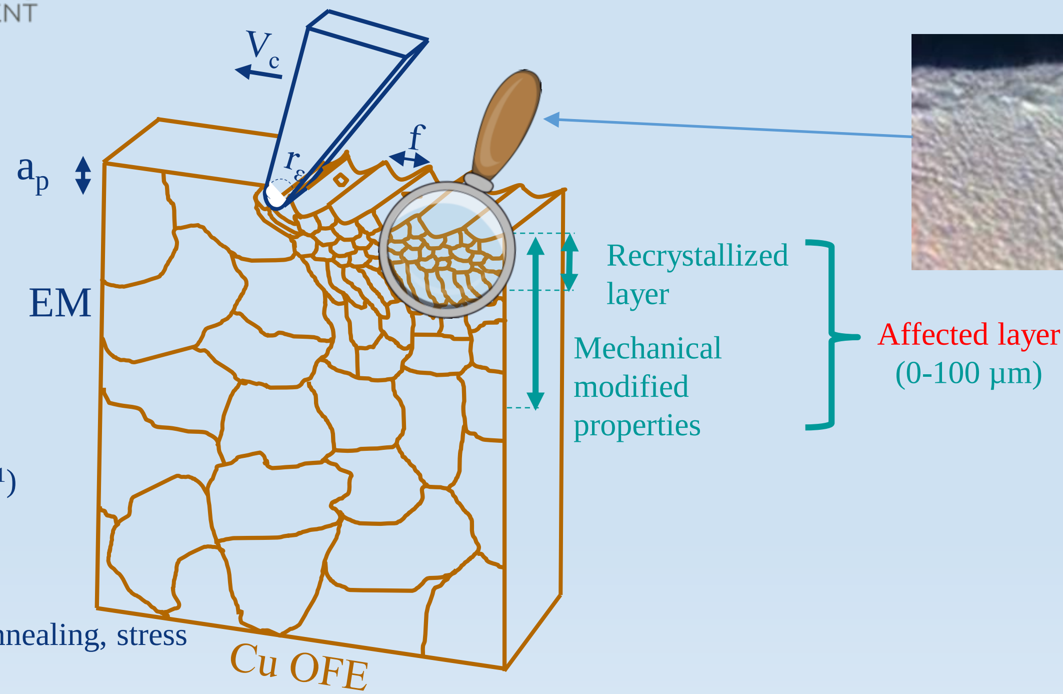


- For prismatic shape
- Interrupted process (many edges cut the material, enter/exit ➔ choc)
  - Thermal and mechanical shocks
  - 5 axis machining for complex shape
    - Programming challenge
    - High precision machine for accurate positioning
- Achievable performance on state-of-the-art equipment
  - Shape accuracy ➔ 10-20 µm
  - Roughness ~ Ra 0.8 µm (SS), Ra 0.2 µm (Cu)





Manufacturing – Affected layer



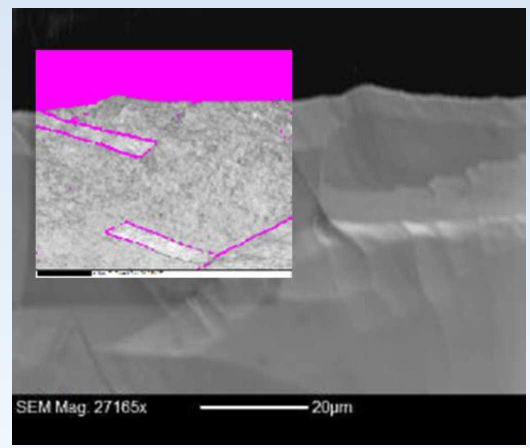
Visible affected layer in case of hard turning parameters.
(a_p = 2 mm, f = 0.35 mm.tr $^{-1}$, V_c = 300 m.min^{-1})

V_c : speed rate (m.min^{-1})
f : feed rate (mm.tr^{-1})
a_p : depth of cut (mm)
r_ε : nose radius (mm)
EM : state of matter (annealing, stress relieving, ¼ hard)

1st results : typical parameters for RF cavities

- Tool : VCGT160404, a_p = 0.3 mm, f = 0.05 mm.tr $^{-1}$, V_c =160 m.min^{-1}, EM = ¼ hard ;
- No recrystallized layer observed ;
- Study on going : development of a way of characterizing affected layer by microscopic analysis ;

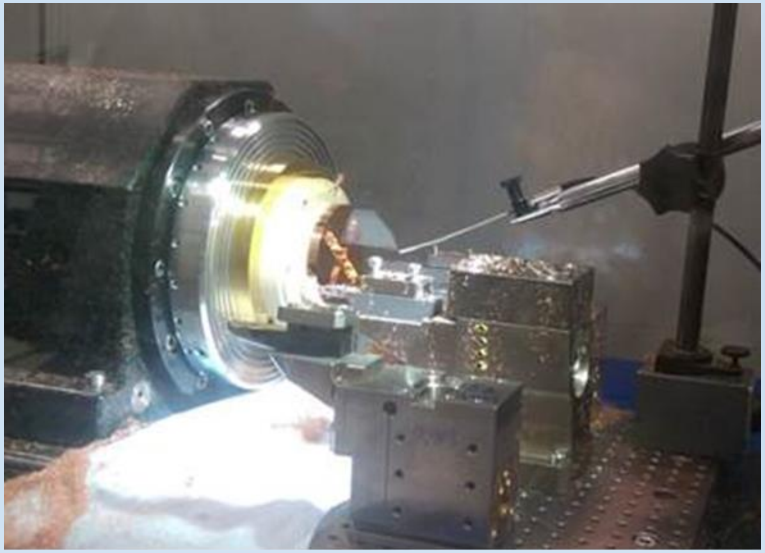
- EBSD / BS (Band Slope) criterion : use to distinguish identical crystalline structure with different density of dislocation => Density of dislocation more significant under surface than in the bulk.
- Nano-hardness measurement and FIB to correlate and validate results

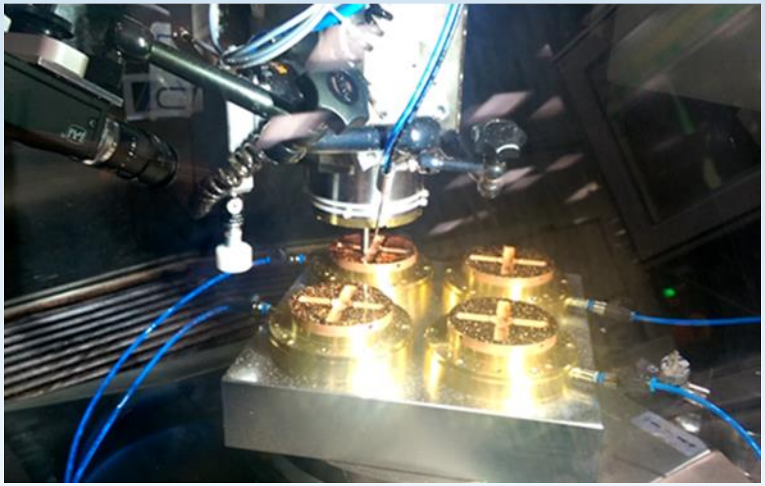


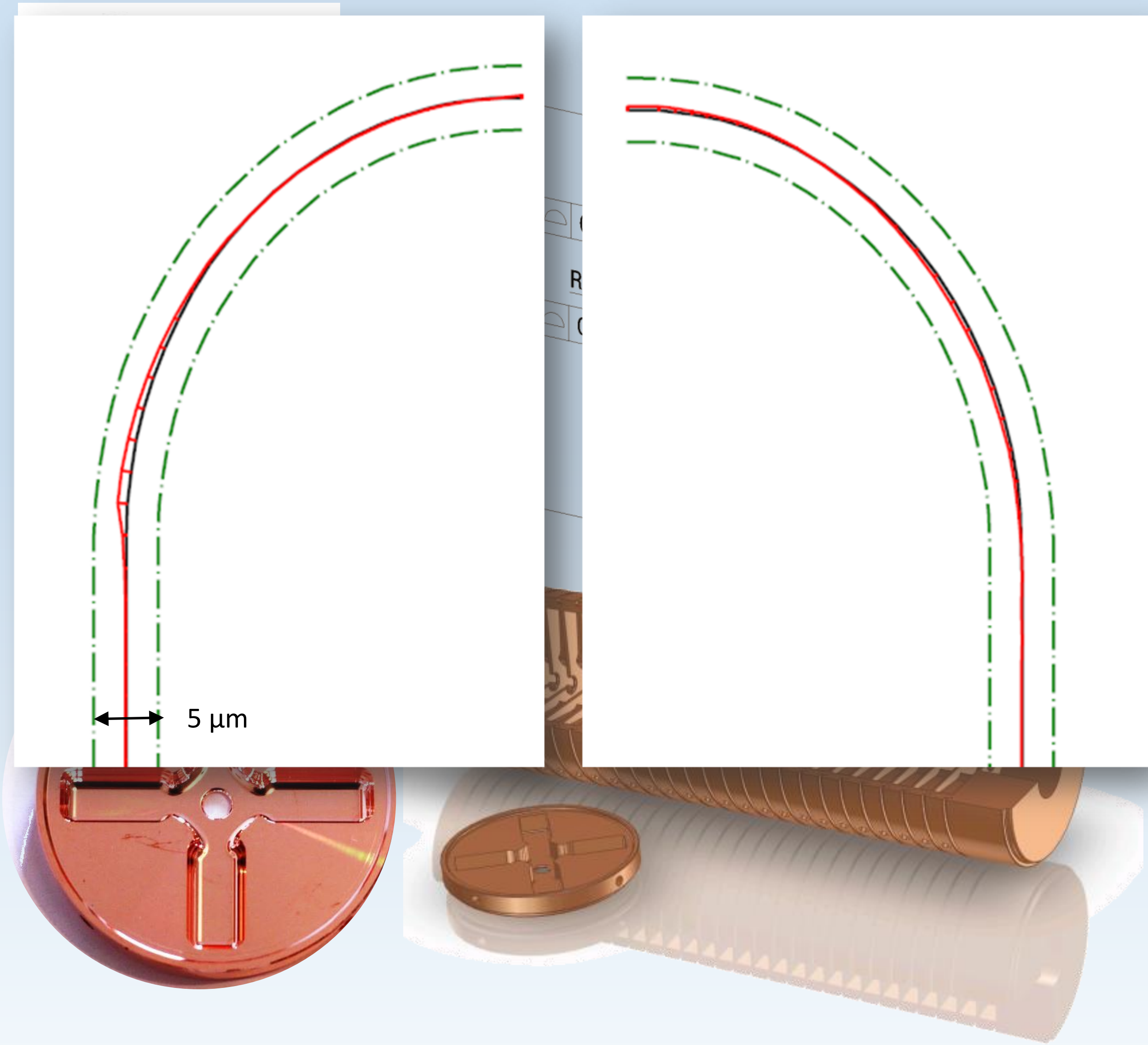
° To be considered, mainly if coating is needed after machining.

° Each machining process has "its" damaged layer!

Manufacturing – Diamond tools ultraprecision Turning / Milling (For non ferrous metals only!)

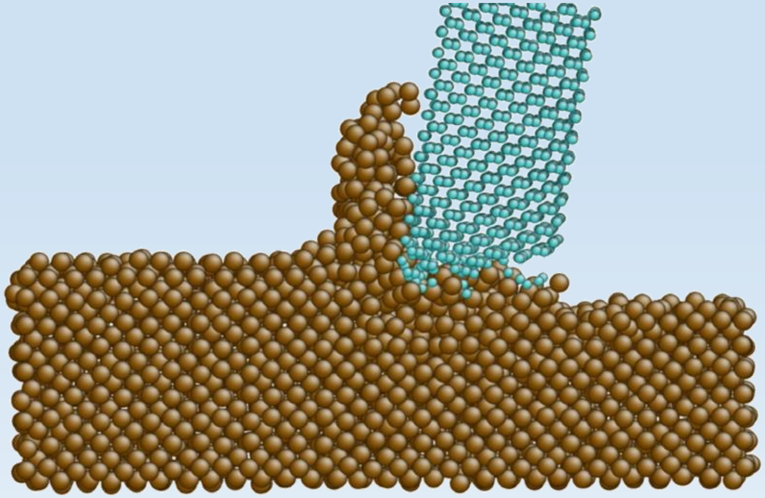






° Diamond cutting is greatly restricted in ferrous material machining because there is a high chemical reactivity between diamond and iron that causes a catastrophic tool wear. The wear process involves the initial transformation of tetrahedral diamond into hcp graphite (graphitization) catalysed by the clean surface of iron and ambient oxygen (oxidation). Finally, there is a diffusion of graphitic carbon into the iron workpiece, quickly eroding the diamond surface. At this stage, diamond tool wear is unstable and impossible to predict with an exact value.

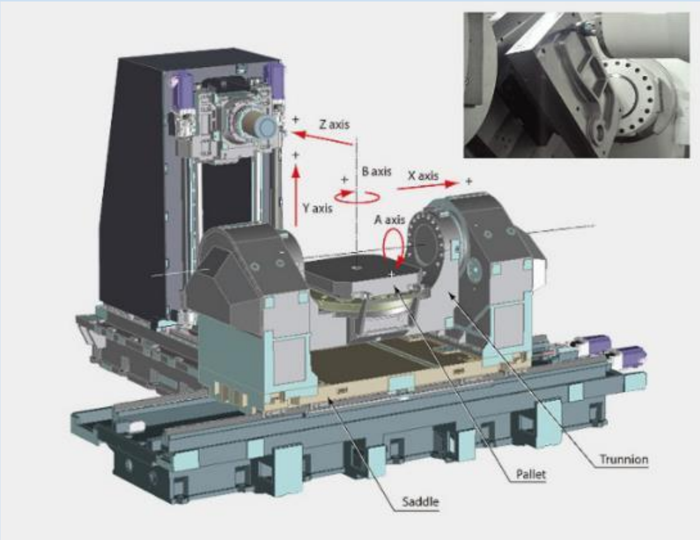
° Diamond turning / milling needs dedicated machine!



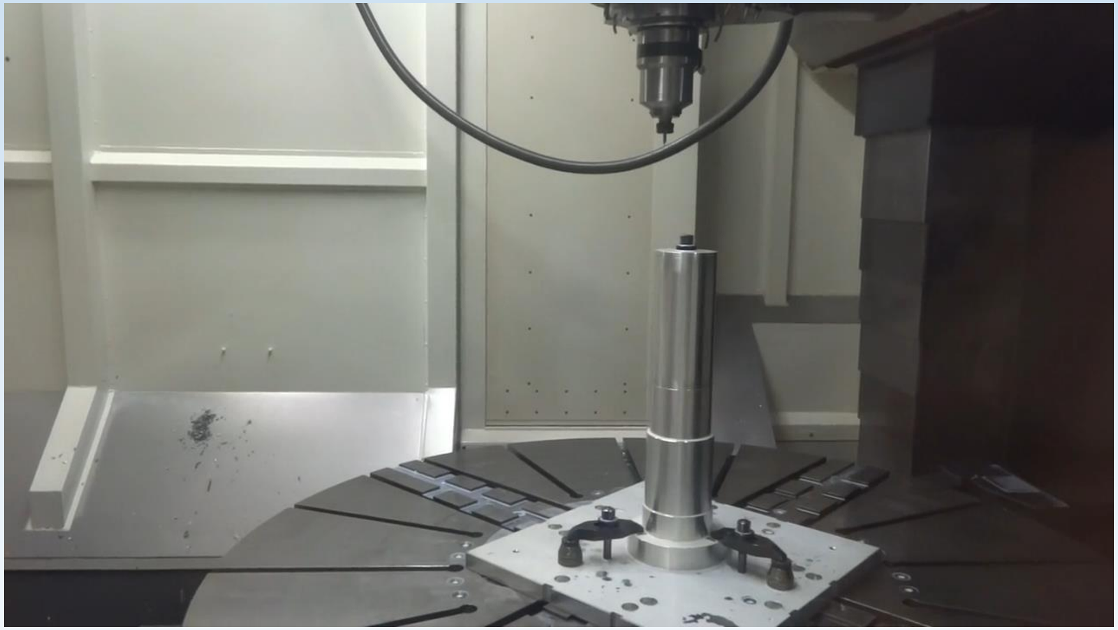
Simulation of graphitic diffusion in orthogonal machining. Carbon atoms are shown in cyan color and iron atoms are shown in ochre colour (Narulkar, Bukkapatnam, Raff, & Komanduri, 2009).

Manufacturing – Milling (Machine) Center

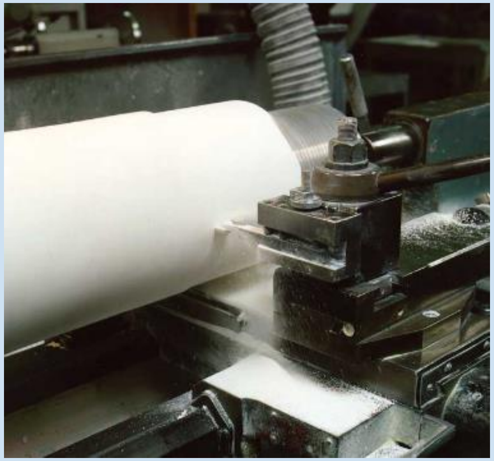
Hermle C42U (CERN)

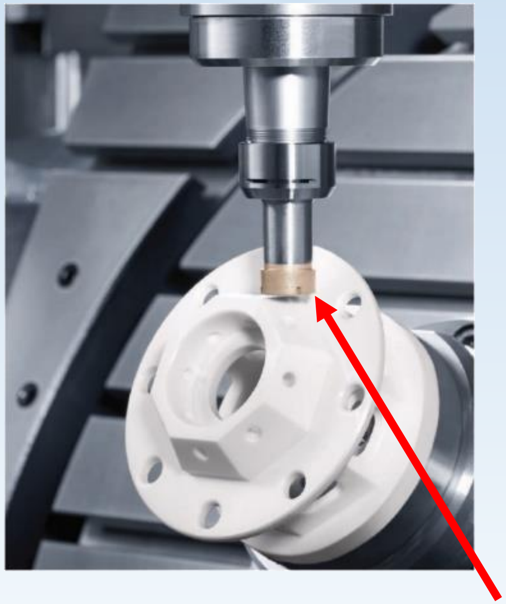


HL-LHC - D2Q4 winding prototype



Manufacturing – Ceramic machining





Diamond tool (cutter)

Manufacturing – Cutting fluids

Ideally, oil-free fluids, fully water soluble, and efficiently removed by solvents – To be tested!

Cleaning

Upon final machining, which uses water soluble non-sulfurous cutting oils, all components are washed in a high temperature detergent bath followed by multiple tap and deionized water rinses. After the last rinse, parts are blown dry with dry nitrogen and packaged. Products are shipped clean and leak tested, ready for high vacuum installation and service.

MDC VACUUM PRODUCTS, LLC

4.1.1 Machining

No lubricant shall be used which might result in material contamination that cannot be removed by the cleaning methods used by the process described here. The use of cutting fluids or lubricants, which contain sulfur or silicone compounds are prohibited. Only water-soluble oils shall be used for machining.

EUROPEAN SPALLATION SOURCE

ESS Vacuum Handbook

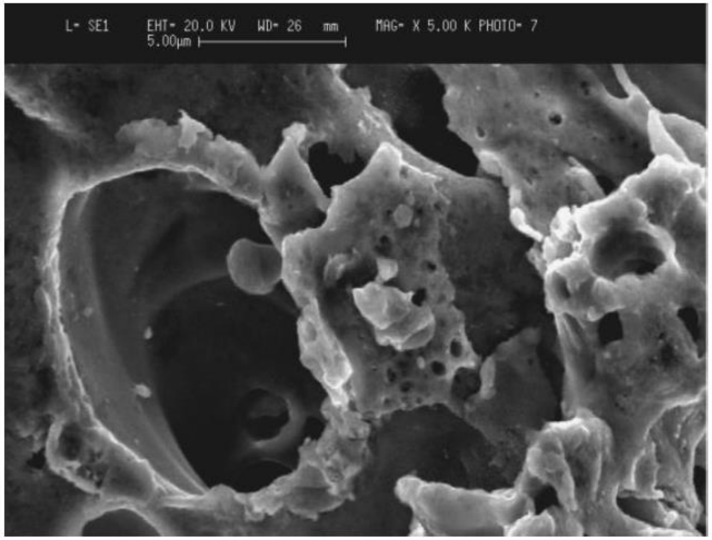
° If possible, finishing by dry-machining or using ethanol as cutting fluid.

° Example: Mineral oil-based coolant, Blasocut BC 35 LF SW, without additives containing sulphur, chlorine, zinc or phosphor. Qualified, by the CERN surface treatment service, as adapted for UHV parts produced by milling and turning.

- Polishing – Or with appropriate material (SiC*, Alumina*, Diamond) , Chemical polishing
  * Caution in case of RF field
- Water, Laser, Plasma cutting – Only for rough machining
- Grinding (abrasive) cutting, honing machining
- Electrical Discharge Machining** (EDM)

** Mainly with wire, and if the wire contains Zn (Brass)!
** Non ideal surface state for vacuum!

Charmilles Technologies Robofil 510 (CERN)



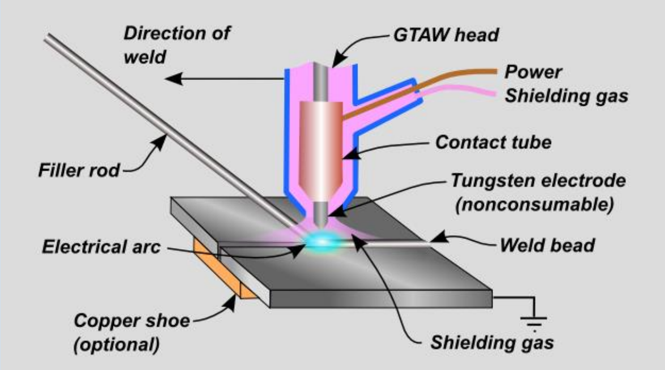
Echantillon I
EDM + solvant 102

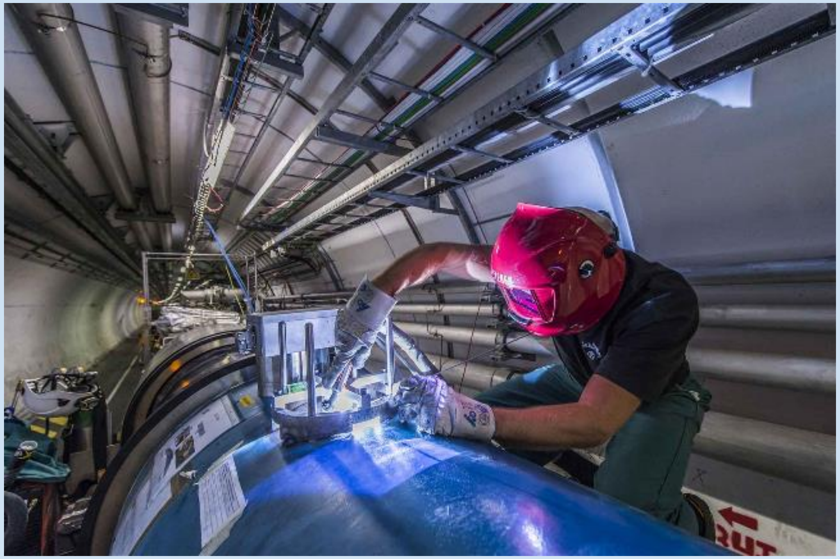
° Spinning – Pressing – Deep drawing – Hydroforming ….

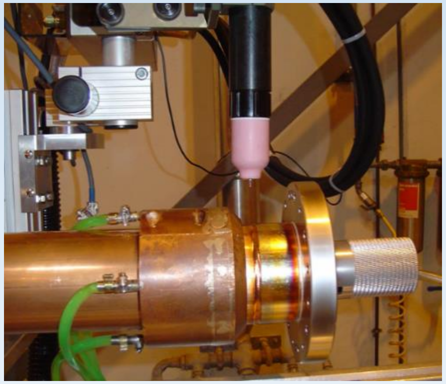
° Extrusions: Significantly reduces deformations and easier the welding operation.

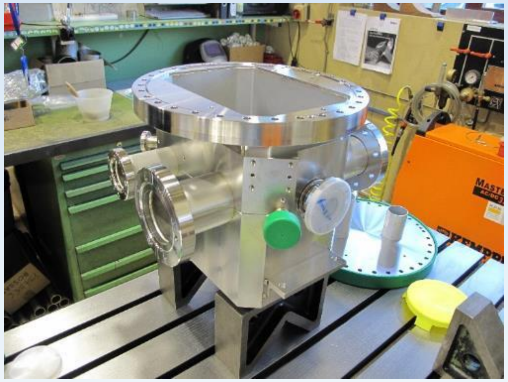
Assembly – TIG welding

- Tungsten Inert Gas welding (gas tungsten arc welding)





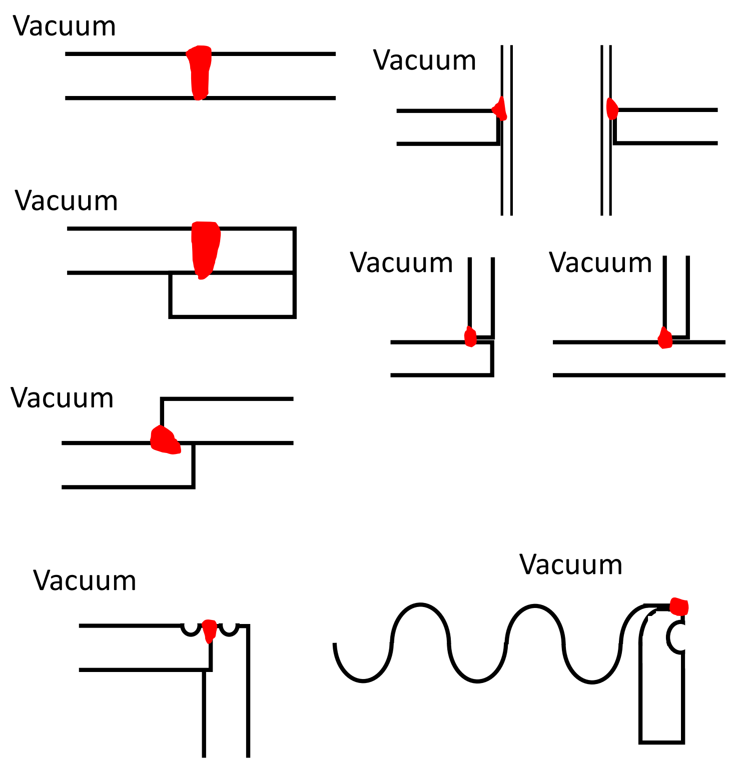




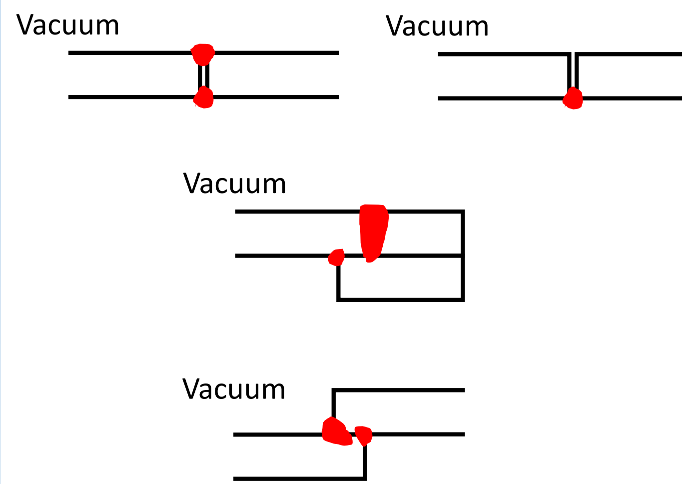
- Tungsten Inert Gas welding (gas tungsten arc welding)

Weld preparation

Correct



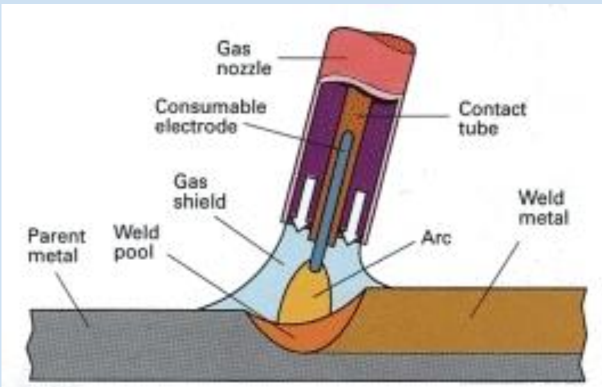
Incorrect

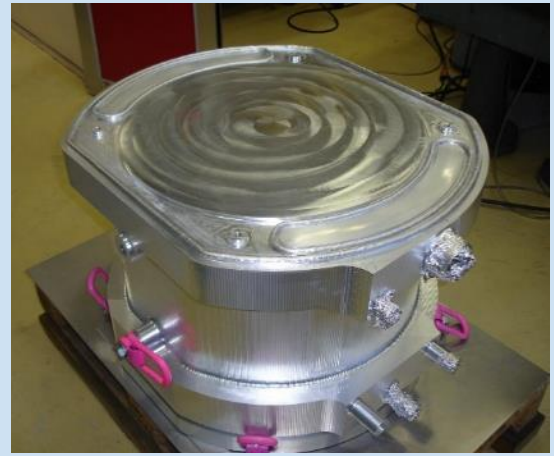


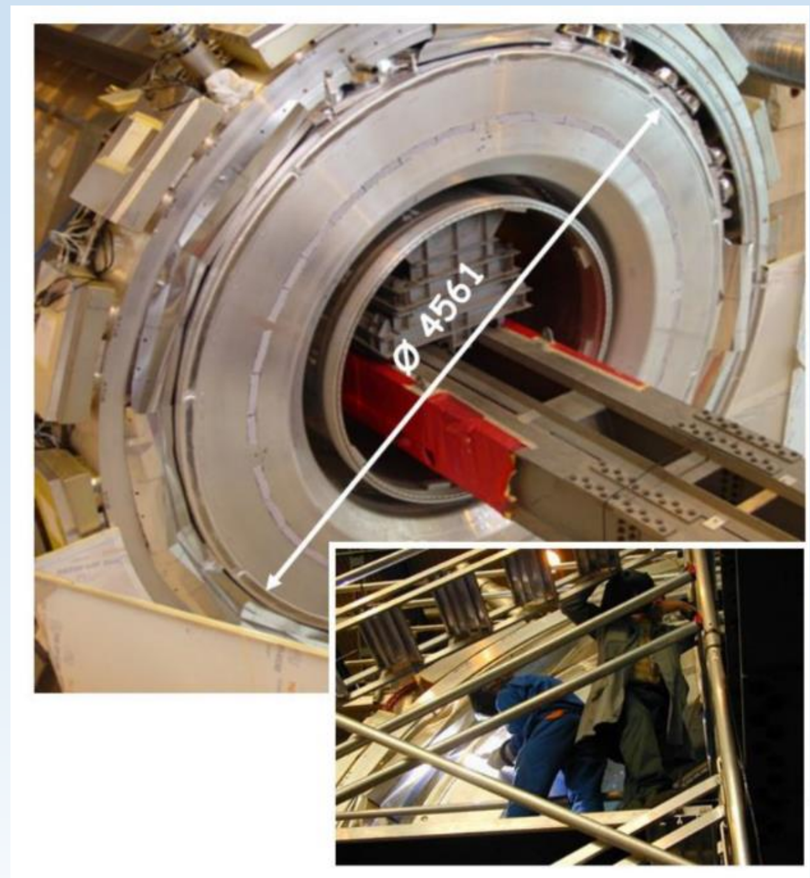
* Air side welding can be accepted if discontinue (for mechanical reinforcement).

Assembly – MIG welding

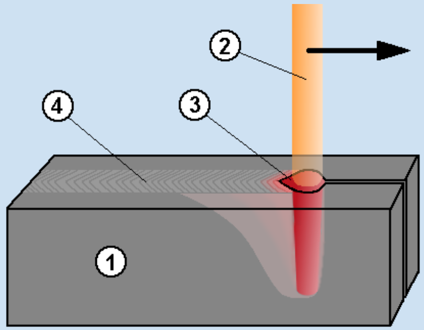
- Metal Inert Gas welding (gas metal arc welding)

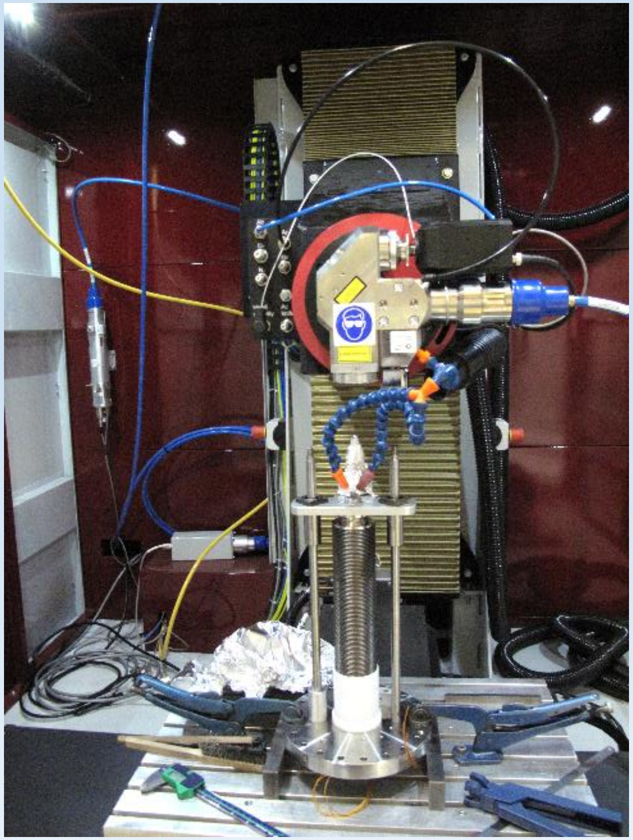






Assembly – Electron and Laser welding

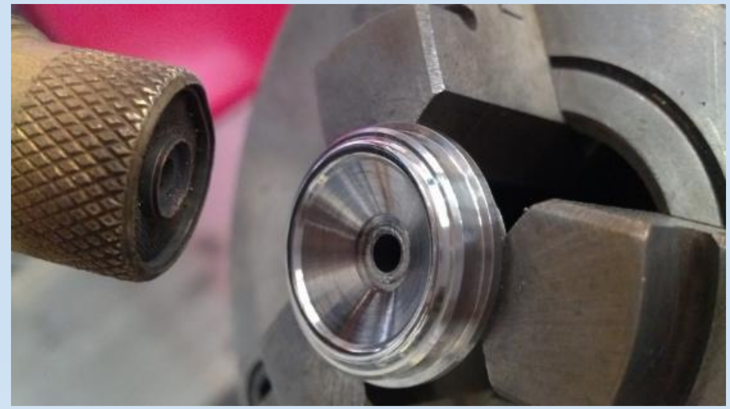




- Electron beam machine (Vacuum chamber)
- Laser beam machine (Gas protection)

Assembly – Electron and Laser welding

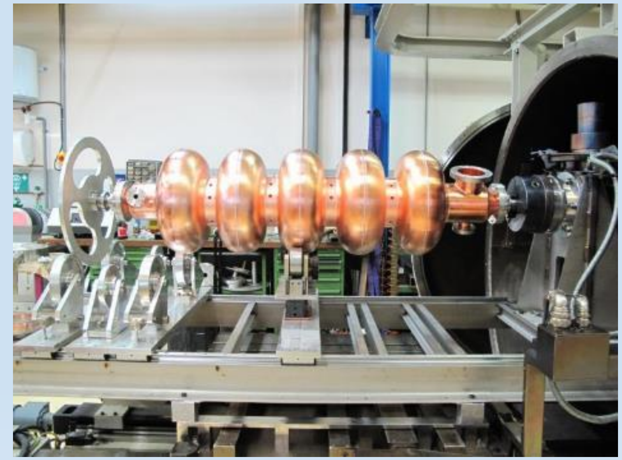
- Laser welding, used for small or large pieces, for high precision welding with limited penetration depth.

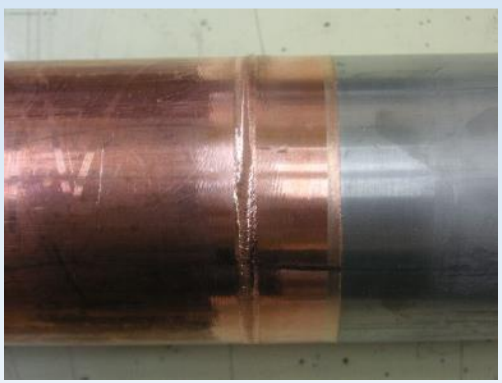


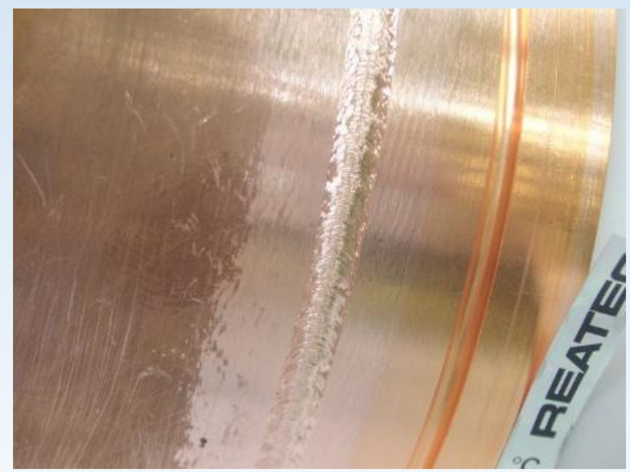
~ 500 spot/m for 4x ~27 km long 20°K capillaries tubes on the LHC beam screen.

Assembly – Electron and Laser welding

° Electron beam welding, for high precision welding or high penetration depth. Welding of large pieces is limited or need special adaptations.

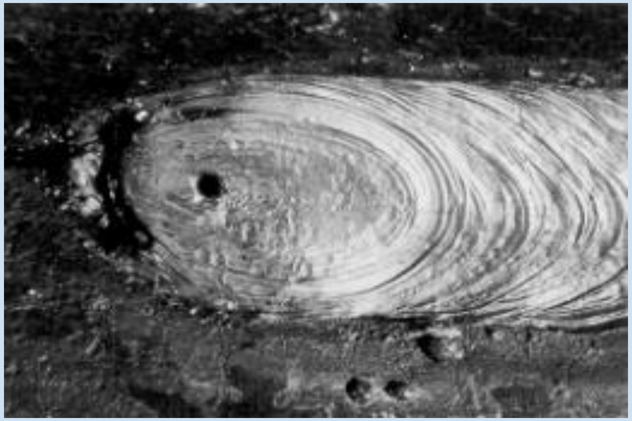




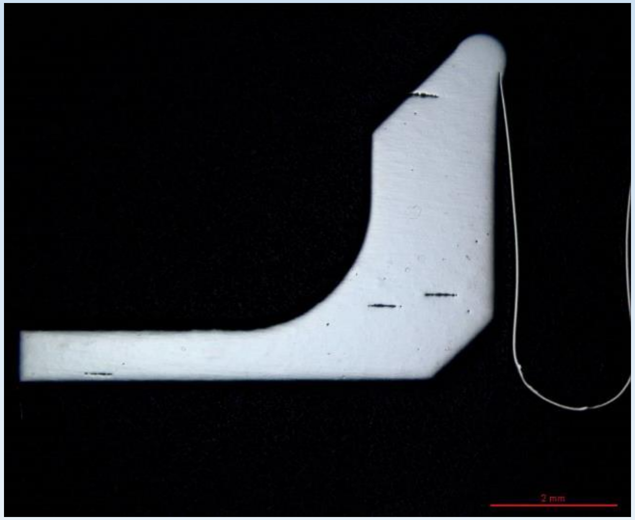


Welding defects*

Hot cracking



Shrinkage holes/voids

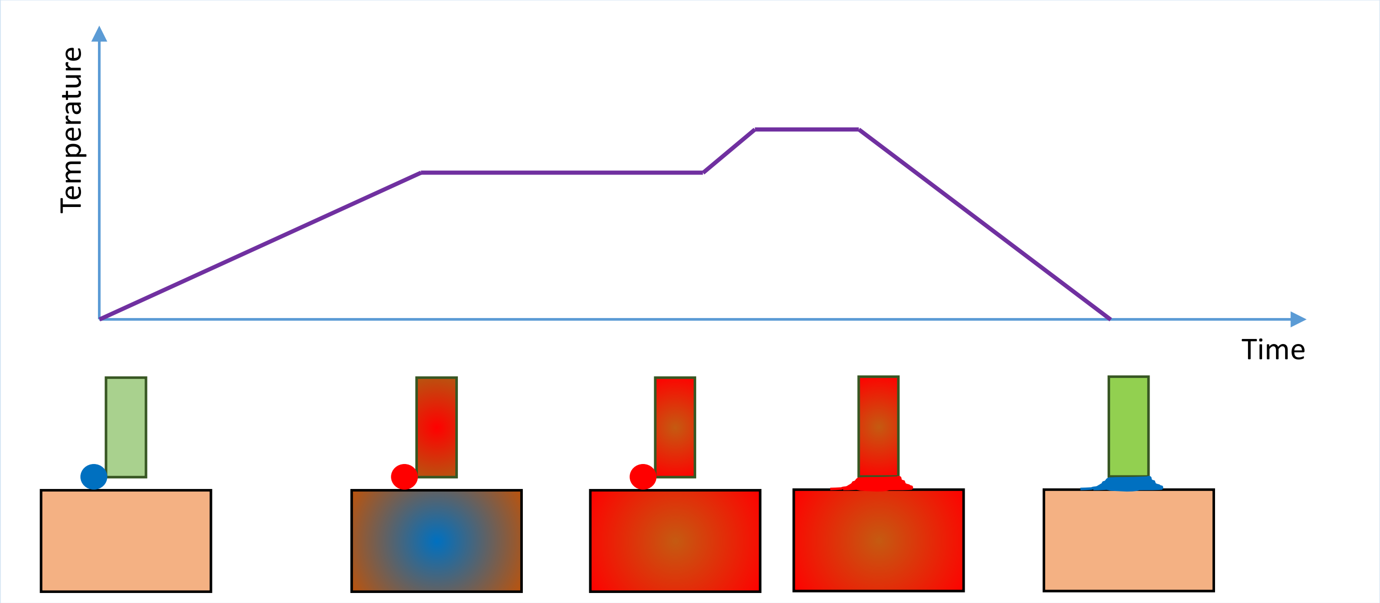


Non metallic inclusions
(Base material defects)

Lack of fusion

Quality of the welding procedure AND of the <u>base materials</u> (purity) are important.

(* see S. Sgobba lecture)



- Brazing & Soldering: Assembly with a filler metal having a melting point lower than for the assembled materials
- Soldering: Melting point of the filler metal < 450 °C, Brazing: > 450 °C.

- Allow the assembly of different metals and no-metals (ceramics).
- Allow high precision assembly.
- Mechanical resistance generally less than for welding.

- Wetting of the filler metal obtained using a flux or with vacuum / reductive atmosphere (and coating if needed).

Air brazing & soldering — Vacuum brazing & soldering

- Main advantage: Oxide reduction at high temperature / low O_2 partial pressure

Gibbs energy of metal oxide formations: **G = H – TS** **H = U + PV**

For the reaction: $2\,Cu_2O \leftrightarrow 4\,Cu + O_2$

$$\Delta G^0 = \Delta H - T\Delta S \quad \rightarrow \quad \Delta G^0 \cong A + BT$$

$$\Delta G^0 = \int \Delta C_p dT - T \int \frac{\Delta C_p}{T} dT$$

For CuO_2, A= -169881 and B= 74.43 [Source: CRC Handbook]

At 800°C, ΔG = -90 kJ → ΔG = -180 kJ for 1 mole of O_2.

At equilibrium, for the production of one mole of O_2:

$$2\Delta G^0_{(T)} = RT \ln \frac{P_{O_{2(eq.,T)}}}{P}$$

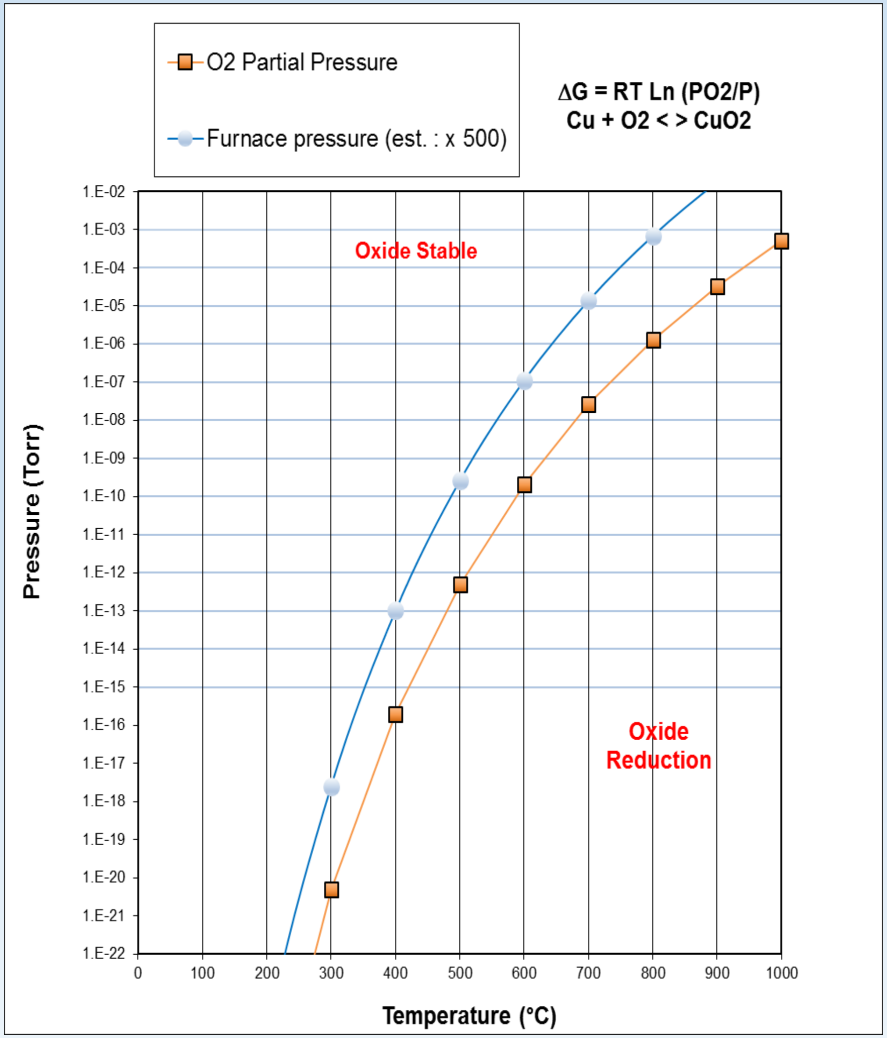
With ΔG = -180 kJ, $\frac{P_{O_{2(eq.)}}}{P} = 1.7\,10^{-9}$

With P = 760 Torr, $P_{O_2(eq.)} = 1.3\,10^{-6} (Torr)$

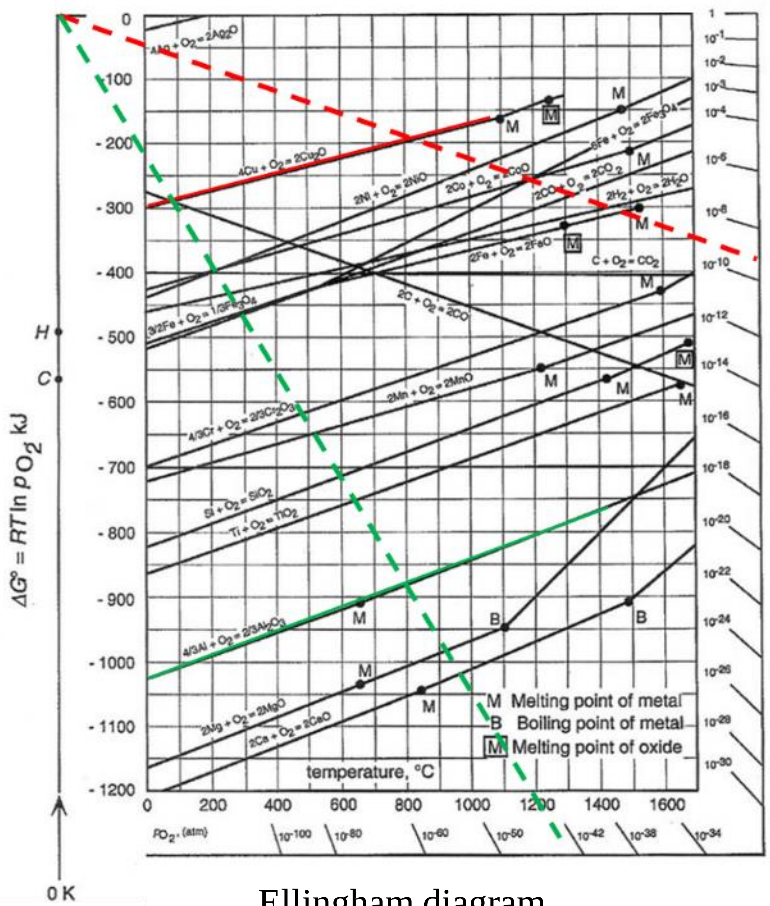
If : $P_{O_2(T)} > P_{O_2(eq.,T)}$ → The oxide is stable

$P_{O_2(T)} < P_{O_2(eq.,T)}$ → The oxide decompose

Assembly – Vacuum brazing



Assembly – Vacuum brazing



Ellingham diagram

$$2\,Cu_2O \leftrightarrow 4\,Cu + O_2$$

For CuO_2, A= -169881 and B= 74.43 [Source: CRC Handbook]

At 800°C, ΔG = -90 kJ → ΔG = -180 kJ for 1 mole of O_2.

With ΔG = -180 kJ, $$\frac{P_{O_2(eq.)}}{P} = 1.7\,10^{-9}$$

With P = 760 Torr, $$P_{O_2(eq.)} = 1.3\,10^{-6}(Torr)$$

$$\frac{2}{3}Al_2O_3 \leftrightarrow \frac{4}{3}Al + O_2$$

For Al_2O_3, A= -1689572 and B= 328.66 [Source: CRC Handbook]

At 800°C, ΔG = -1337 kJ → ΔG = -891 kJ for 1 mole of O_2.

With ΔG = -893 kJ, $$\frac{P_{O_2(eq.)}}{P} = 3.4\,10^{-44}$$

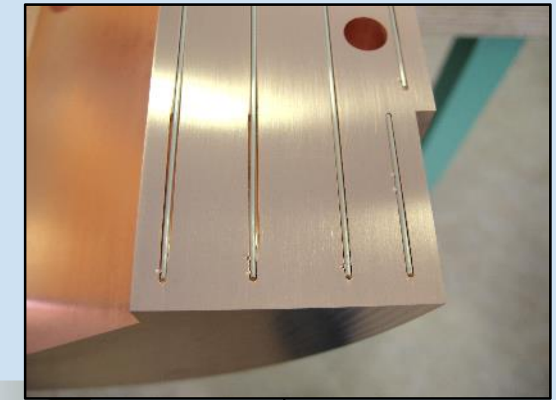
With P = 760 Torr, $$P_{O_2(eq.)} = 2.5\,10^{-41}(Torr)$$

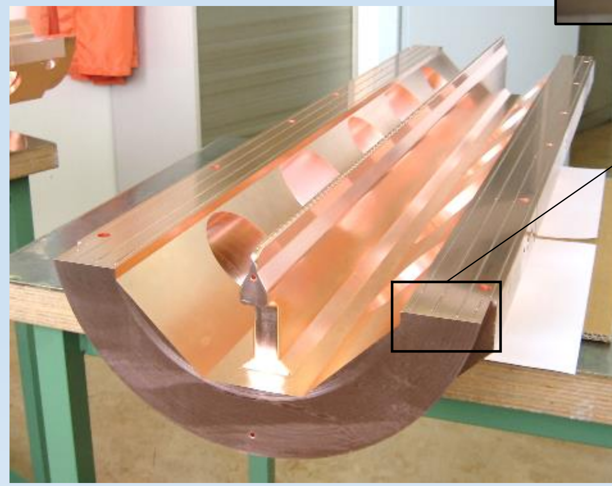
Assembly – Vacuum brazing

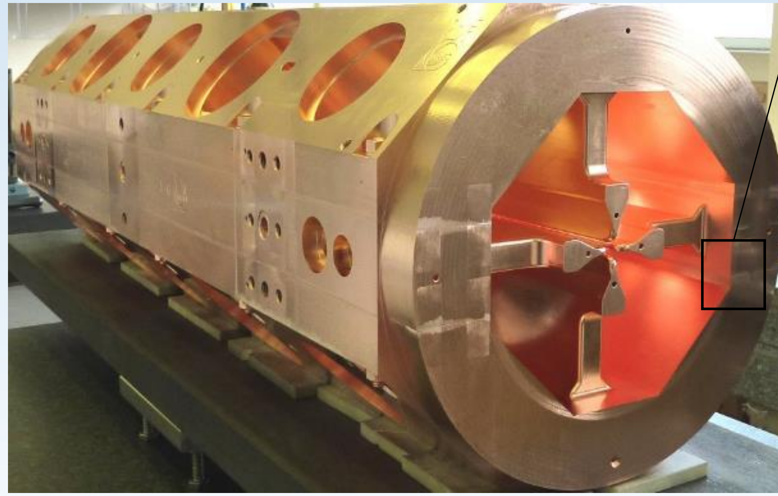
° Wetting is generally excellent.
° Brazing on large surfaces possible.
° Allow very good thermal and electrical contacts.
° Assembly clean and UHV compatible.
(Filler metal and material with low vapor pressures!)
° Dissimilar materials can be join.
° Allow high precision assembly with little or no distortion of the components

But:
° Heat treatment can affect the properties of the base materials.
° Mechanical tolerances are tight

Filler Metal	Gap *(mm)*	Ideal *(mm)*	Brazing Temp. *(°C)*
Cu	0-0.05	0.025	>1083
Ag-Cu (Pd)	0-0.05	0.025	795 - 820
Au-Cu	0.03-0.1	0.05	>920
Ni-Cr	0.03-0.1	0.05	>1050



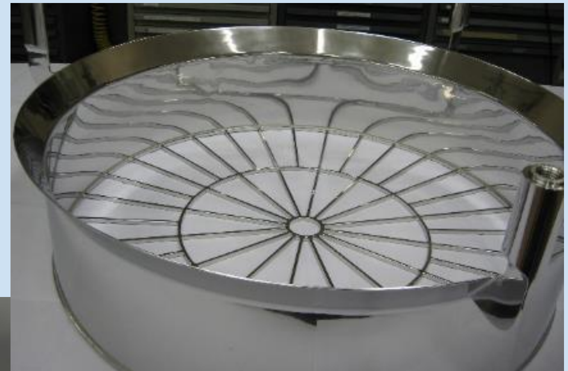


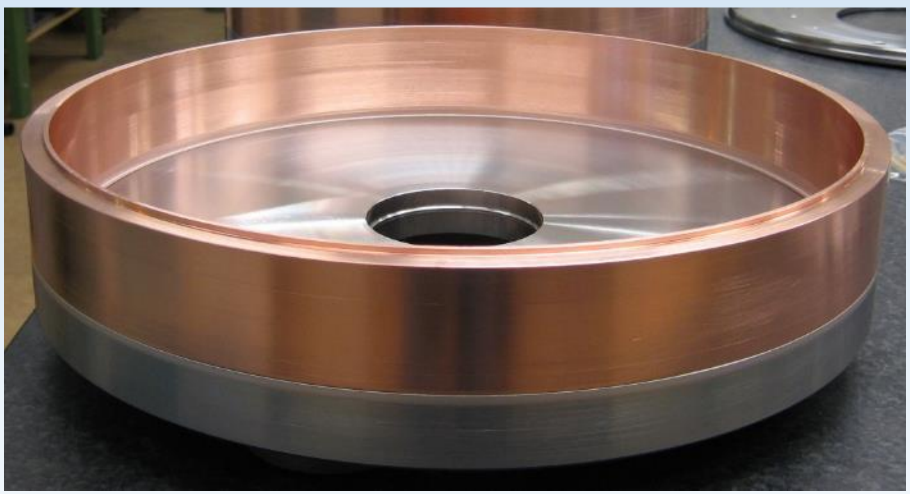


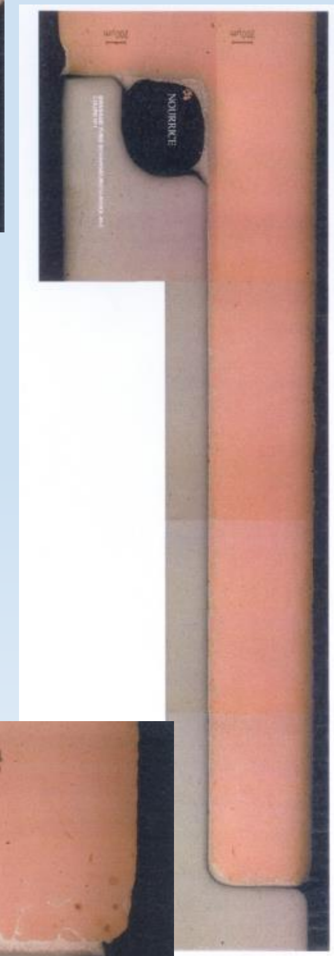
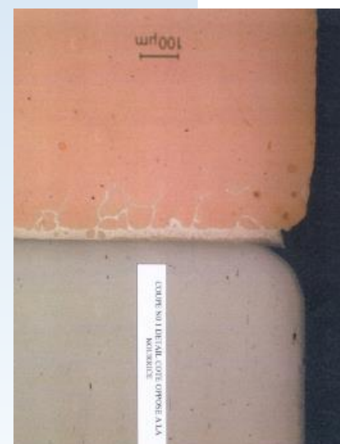
Filler metal seen on the vacuum side

Assembly – Vacuum brazing

° Joint configuration:
- Groove, no gap (Ra ≈ 0.8 µm)
- Groove on a diameter
- Chamfer
- Foil
- Paste





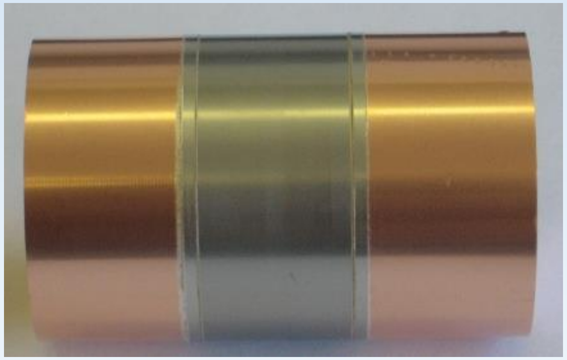
Assembly – Vacuum brazing

- Dissimilar metals:

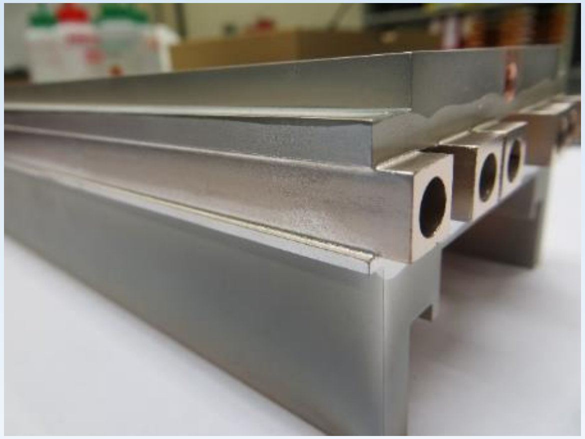
Nb – Stainless steel

Mo – Stainless steel

Be - Cu – Stainless steel



Cu – Stainless steel - Ti



Glidcop - CuNi

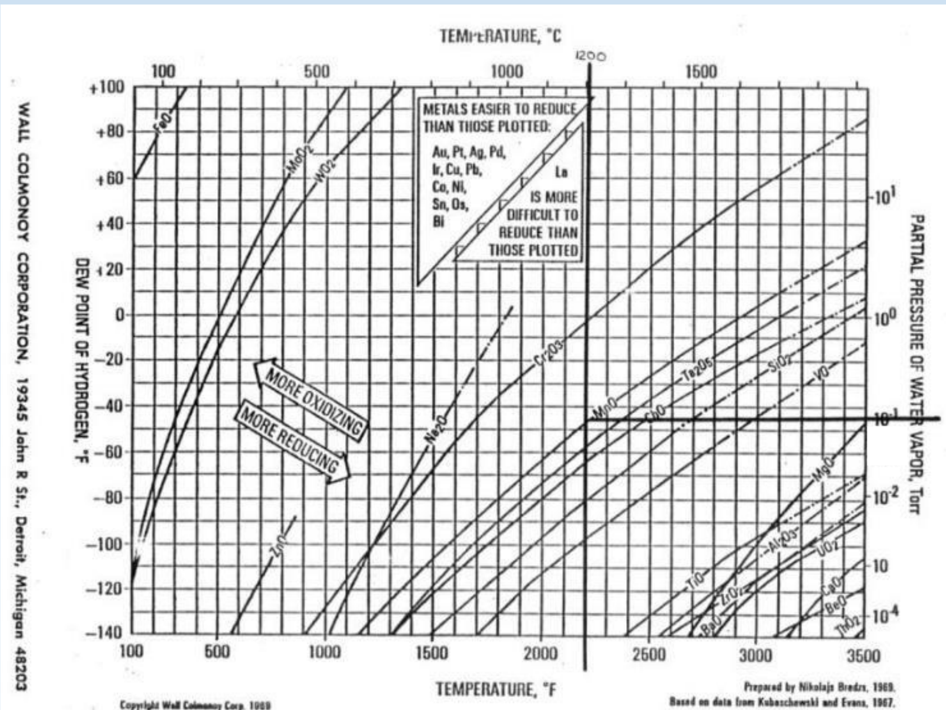
Cu – W

° Ceramic (Alumina) / metal brazing:

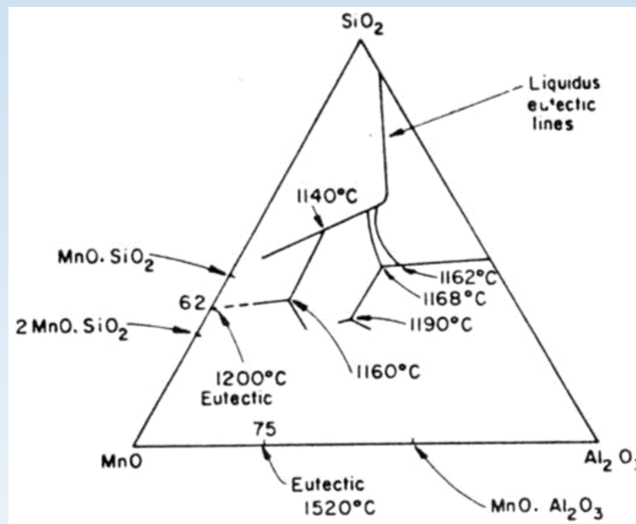
First process = Mo-Mn metallization

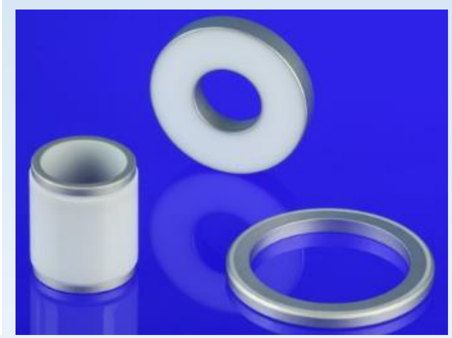
Mo + MnO (Mn) powder on alumina (Al_2O_3) @ T > 1200 °C and P_{H2O} / P_{H2} > 10^{-4} induce:

- Mo reduction and $MnO/Al_2O_3/SiO_2$… vitreous phase formation.
- Interaction with the Alumina base material and the binder.
- Sintering of the Mo powder in the vitreous phase during cooling.
- Formation of Mo-Mn layer strongly adhering the support.
- Ni layer added to improve the brazing.



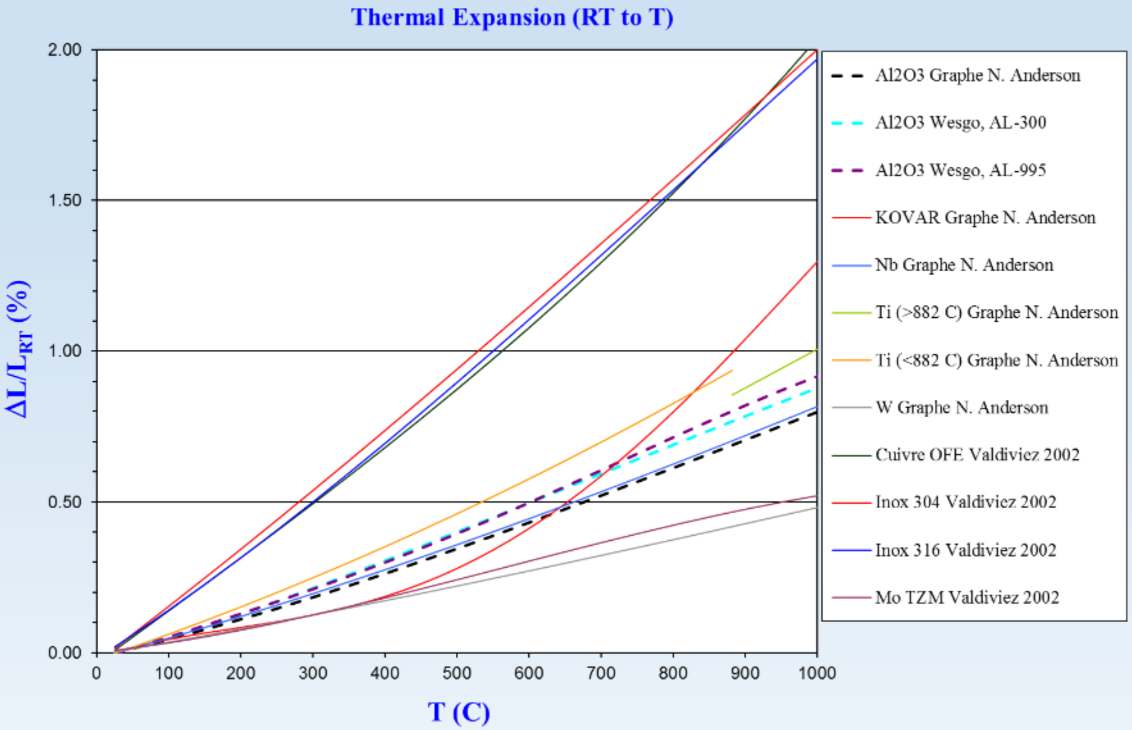
4. Metal-metal oxide equilibrium in pure hydrogen atmospheres as a function of dew point showing molybdenum to be present always as the metal and manganese always as the oxide.





° Ceramic (Alumina) / metals brazing: First process = Mo-Mn metallization

Metal thermal expansion AND metal yield strength should be take into account for Metal / Alumina brazing.



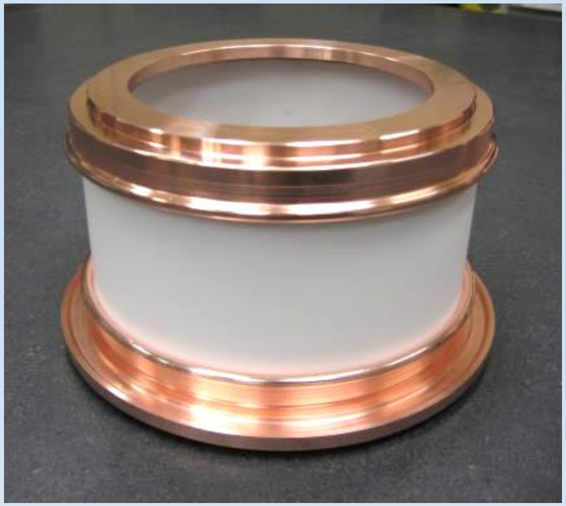
Métal	TCF
Niobium	88
Platine	33
Tantale	28
Cuivre	20
Titane	8.8
Kovar	7.7
Nickel	6.7
CuNi	4.8
Fe-42Ni	4.5
Monel	4.0
Invar	3.7
Molybdène	3.5
Inox 304	2.9
Inconel 600	2.1
Tungstène	2.0

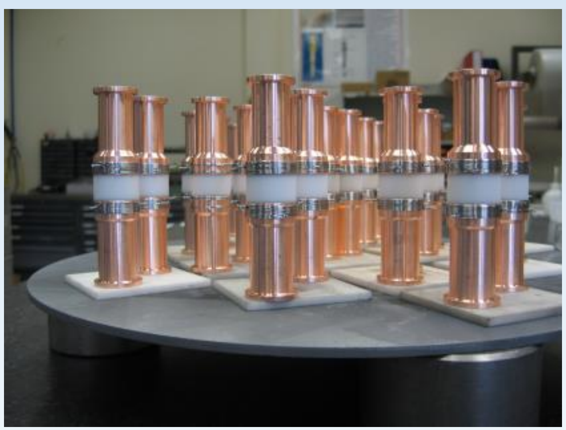
Higher Thermomechanical Compatibility Factor (TCB) means reduced stress after brazing.

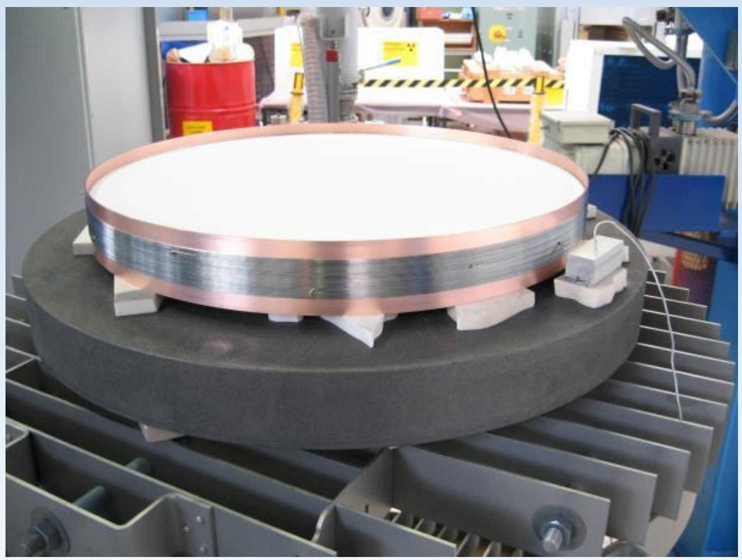
Assembly – Ceramic / metal vacuum brazing

° Brazing on MoMn metallized Alumina

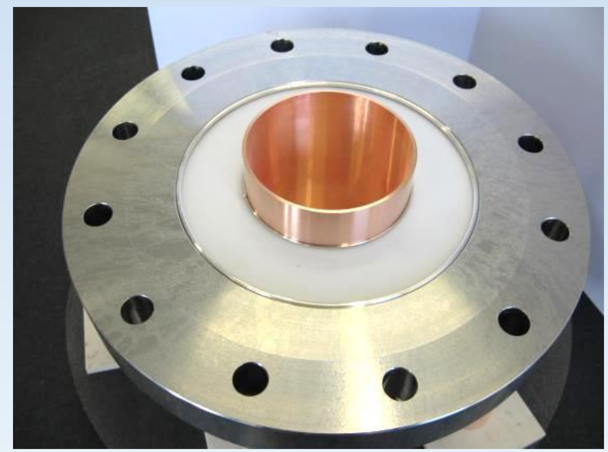
Kovar (Dilver) – Alumina







Cu – Alumina (up to diameter 400 mm!)



Ti – Alumina – Cu

Assembly – Ceramic / metal vacuum brazing

° Ceramic / metal brazing:

Second process = Active Brazing

- Brazing alloy containing reductive metal: Ti, Zr, Be, …

- At brazing temperature, under high vacuum, strong interaction with oxides (alumina), carbide, nitrite, ….

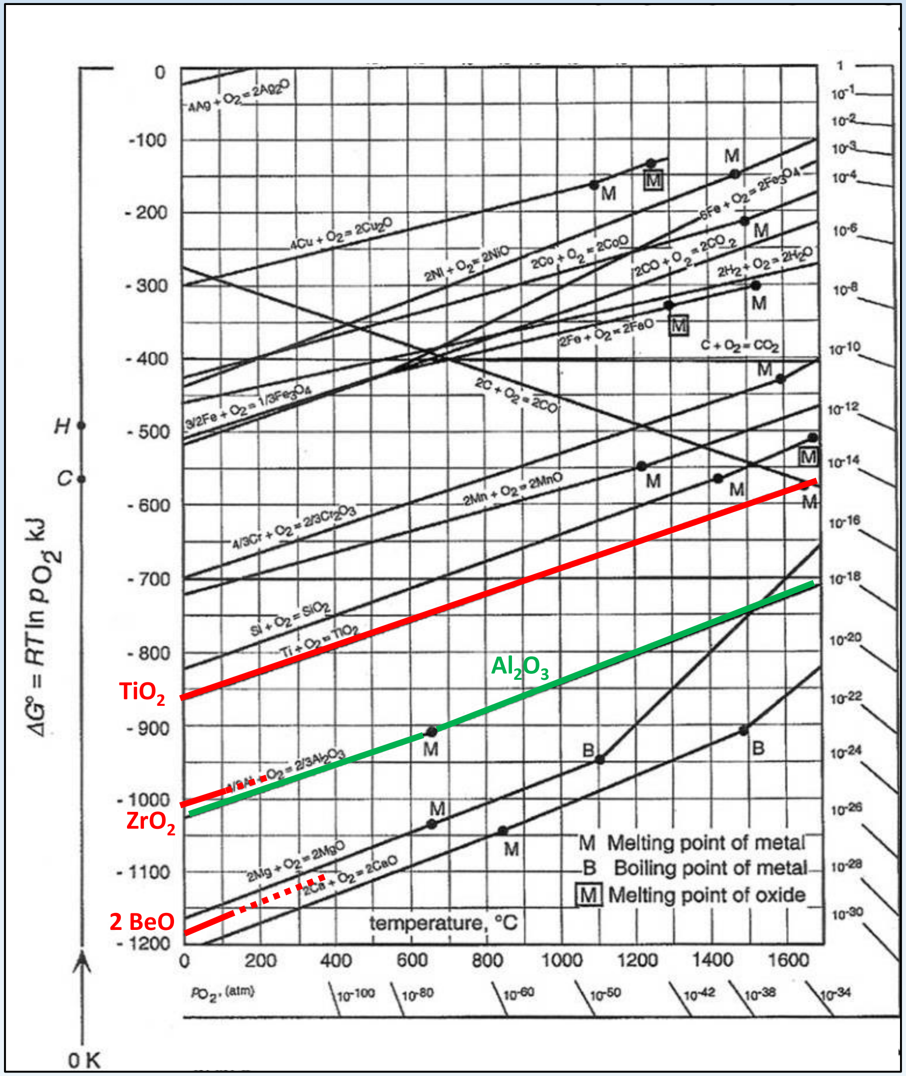
- Complex chemical reactions formed at the ceramic / brazing metal interface. Ex.: SiC/Ti > Ti_3SiC_2, Ti_5Si_3C, $Ti_5Si_3C_x$,….

- ↑ Interaction (wetting) possible with several types of ceramics.

- ↓ Possible formation of brittle phases.

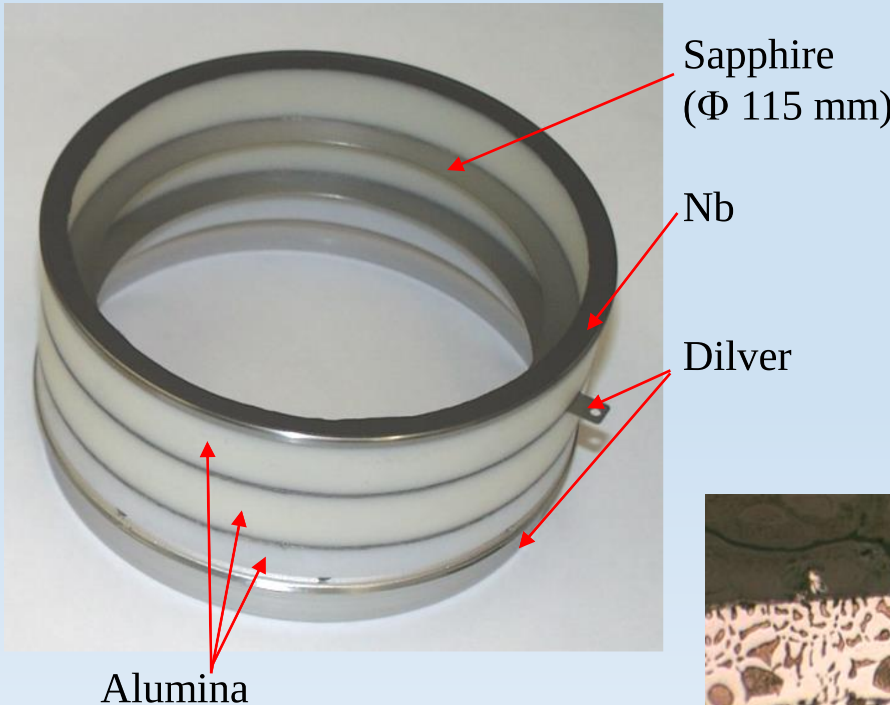
- Example of Active Brazing Alloys:

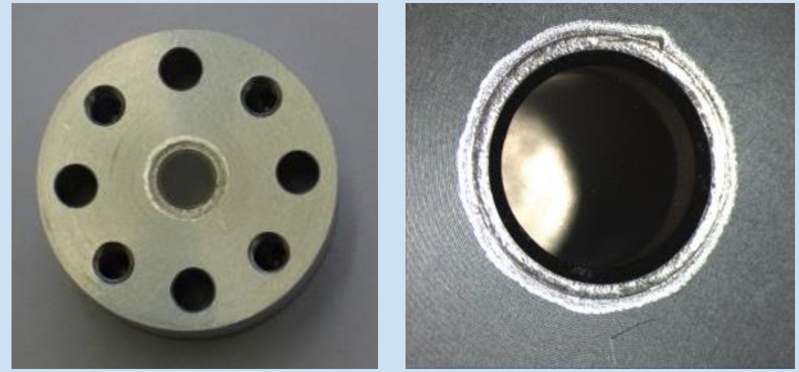
CuSil ABA (Ag 63, Cu 35.25, Ti 1.75)
Silver ABA (Ag 92.75, Cu 5, Al 1, Ti 1.25)
Gold ABA (Au 96.4, Ni 3, Ti 0.6)



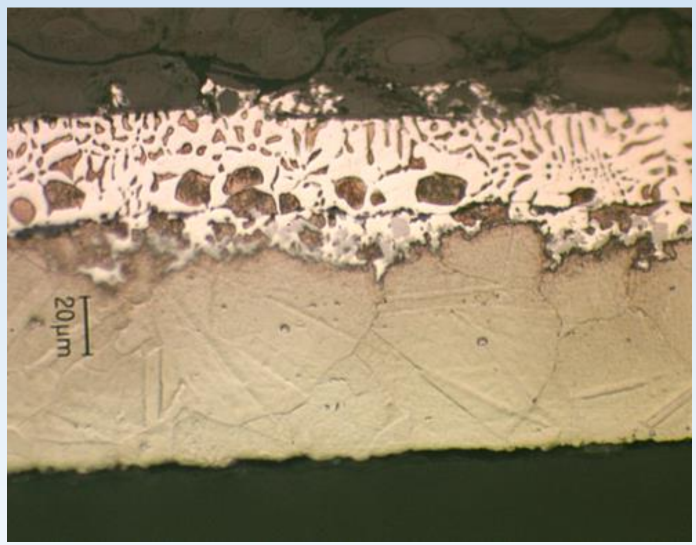
Ellingham diagram

- Active brazing on ceramics





Diamond (Φ 5 mm) – Ti



Carbon – CuSil ABA – CuNi

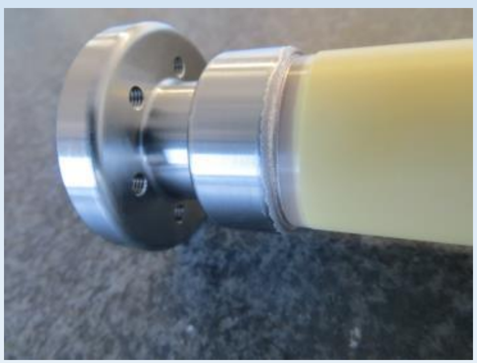
AlN – Dilver

Assembly – Ceramic / metal vacuum brazing

- Active brazing on ceramics

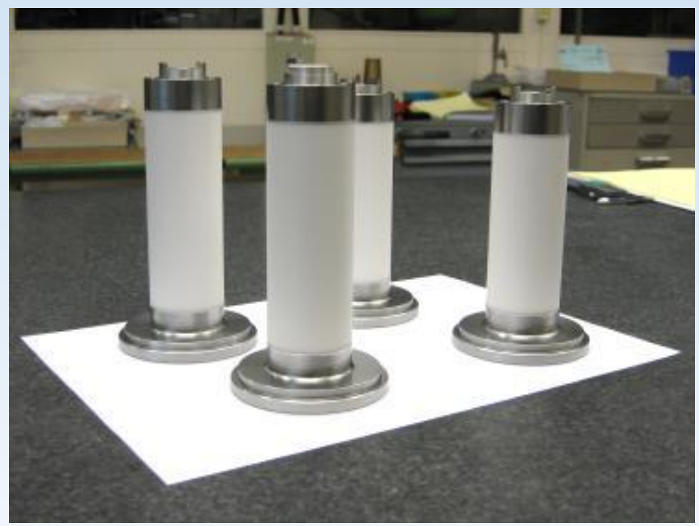
Alumina – Ti

Alumina – Cu



ZrO_2 – Ti

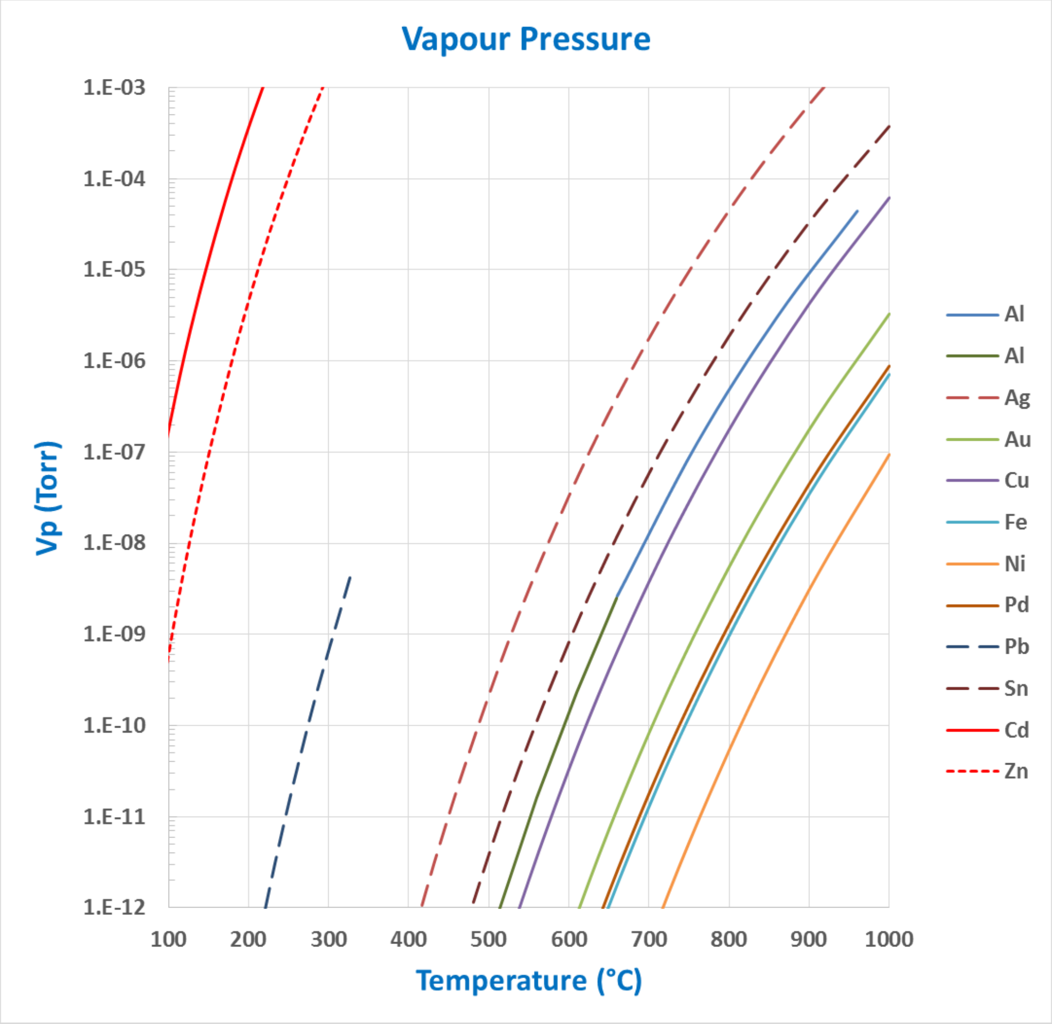
Alumina – Monel



Alumina – Ti

Assembly – Vacuum soldering

° High purity SnAg or SnPb solders can be used in vacuum …



- Typical solders:

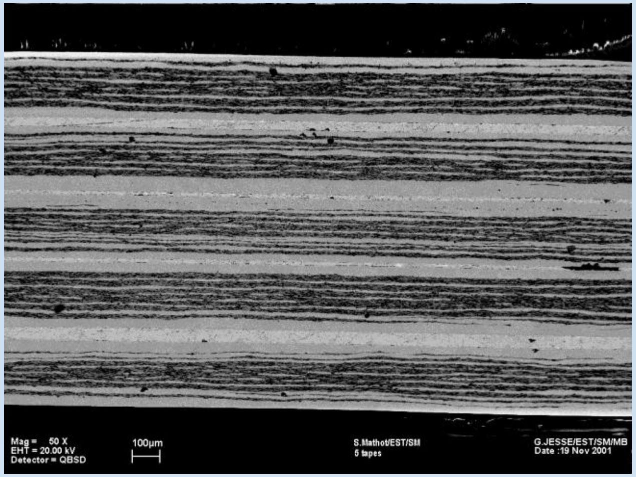
  SnAg (eutectic): m.p. 221°C
  SnPb (eutectic): m.p. 183°C

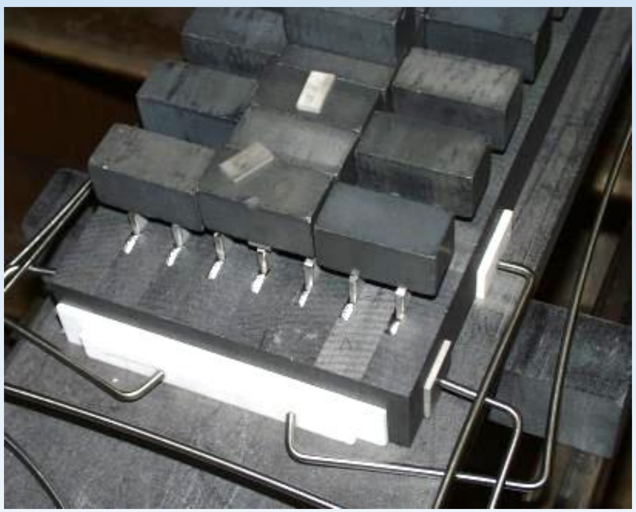
- Wetting acceptable on:

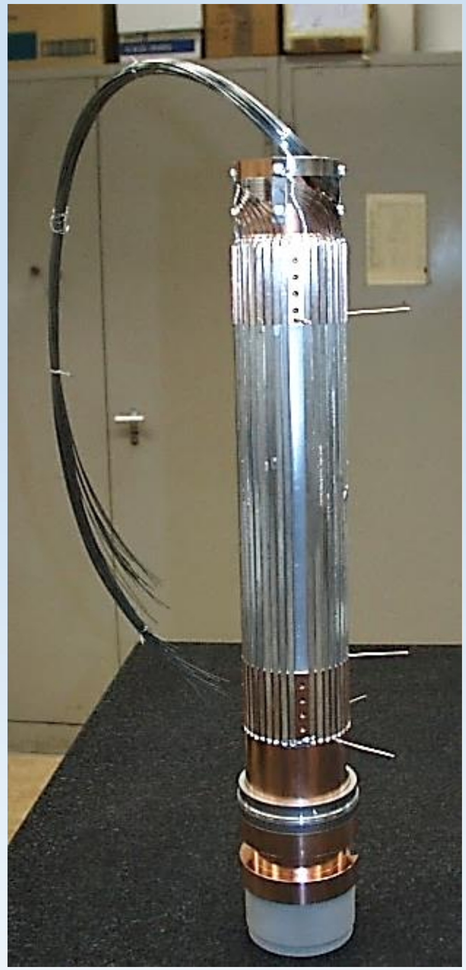
  Cu and Ag

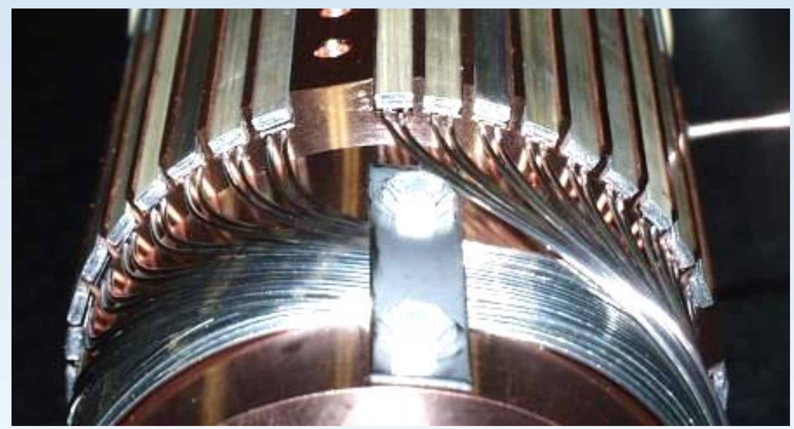
Assembly – Vacuum soldering

- Example: Vacuum soldering of High Temperature Superconductor (HTS) tapes for the LHC current leads.





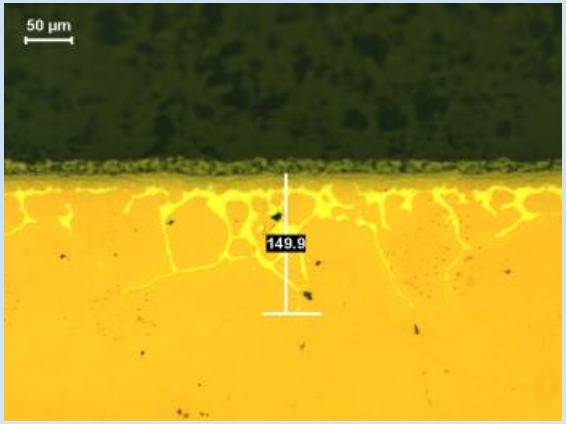


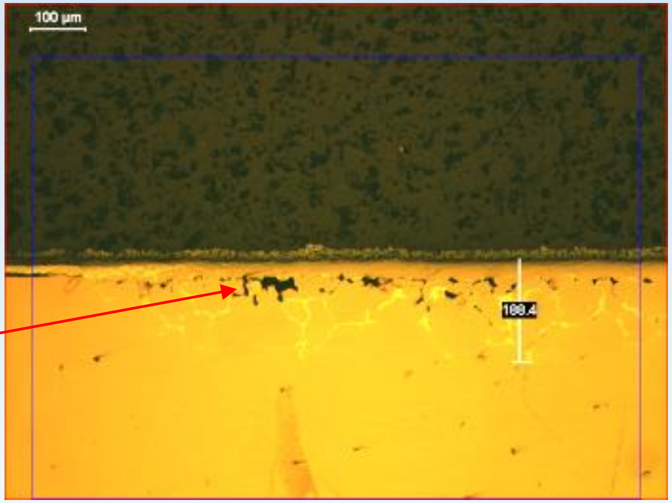


HTS tapes soldering – SnAg

HTS stacks soldering – SnPb

° Diffusion brazing: The filler metal is form by diffusion during the heat treatment.





Porosities

° Diffusion bonding: Interface between materials disappears by solid state diffusion at high temperature and high contact pressure.

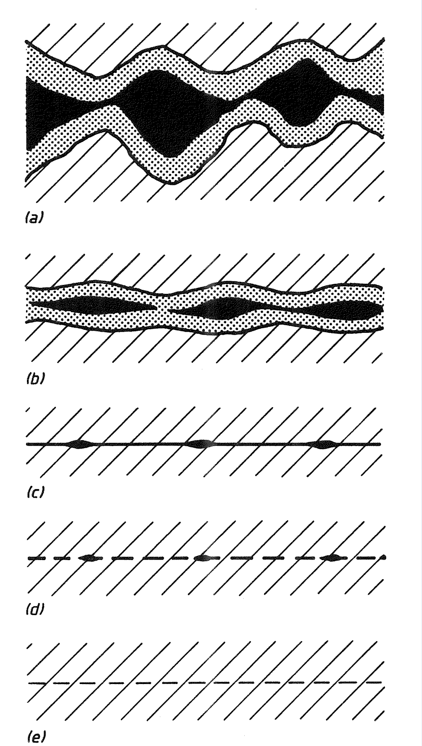
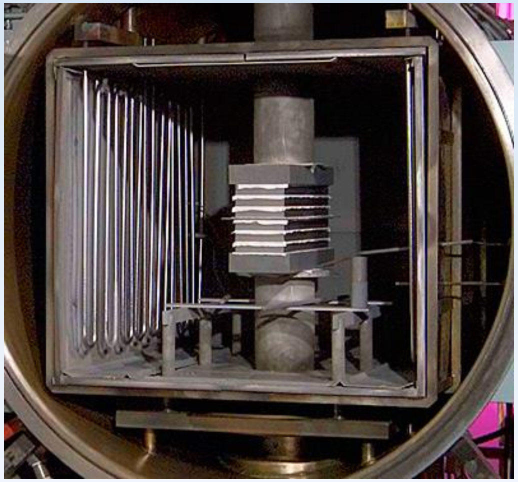
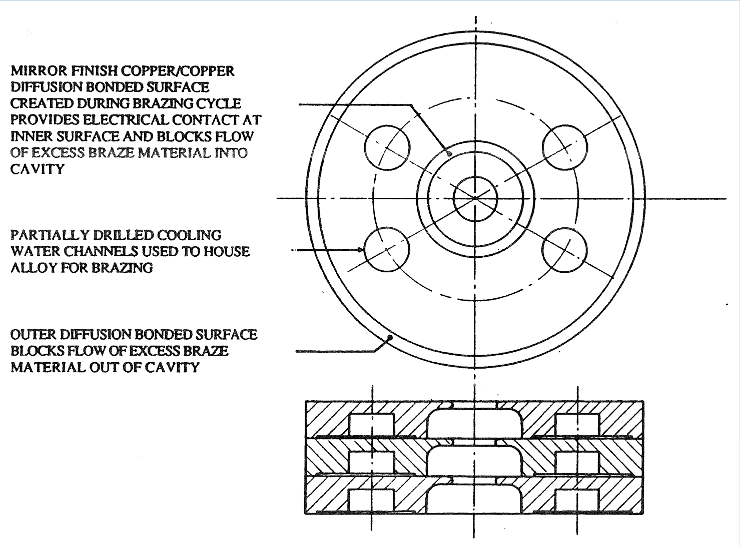


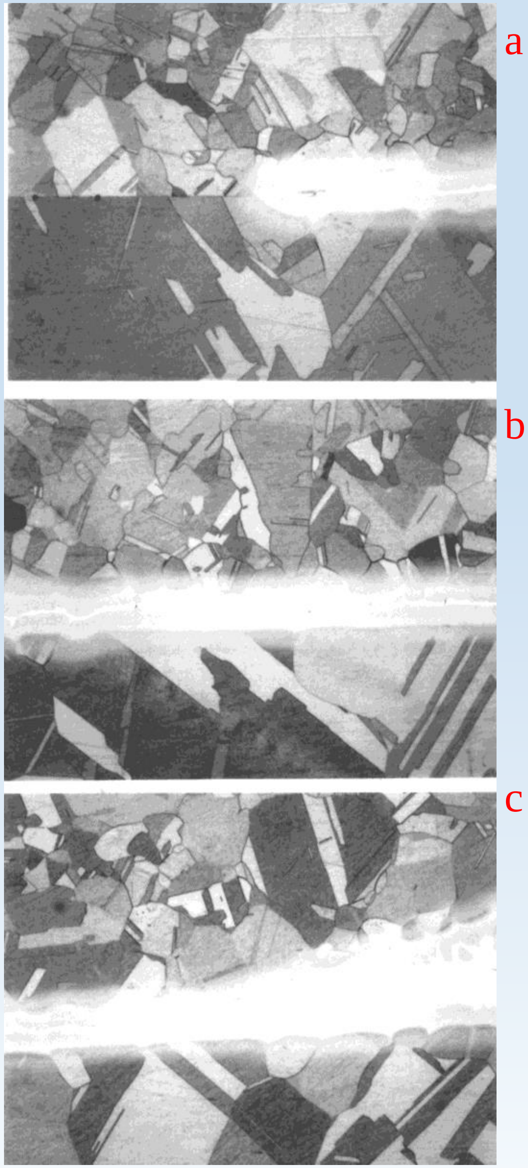
Fig.1 The mechanism of diffusion bonding:

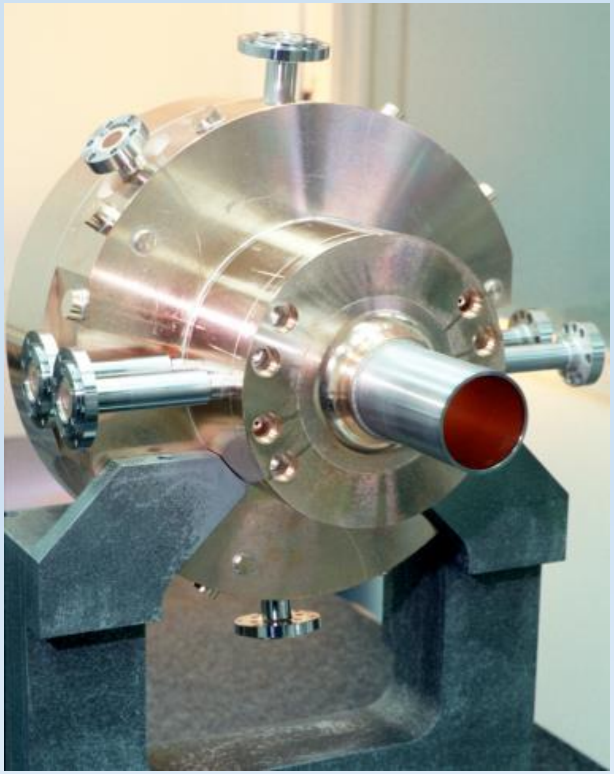
a) *Initial 'point' contact and oxide contaminant layer;*
b) *After some 'point' yielding and creep, a thinner oxide layer, large voids;*
c) *After final yielding and creep, some voids remain with very thin oxide layer;*
d) *Continued vacancy diffusion eliminates oxide layer, leaves few small voids, until*
e) *Bonding is complete.*

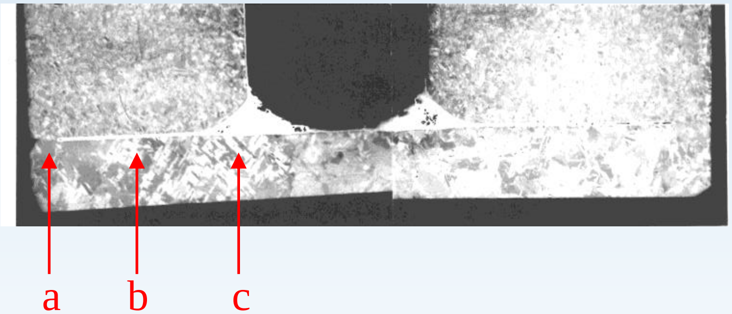


° Brazing & Partial Diffusion Bonding:

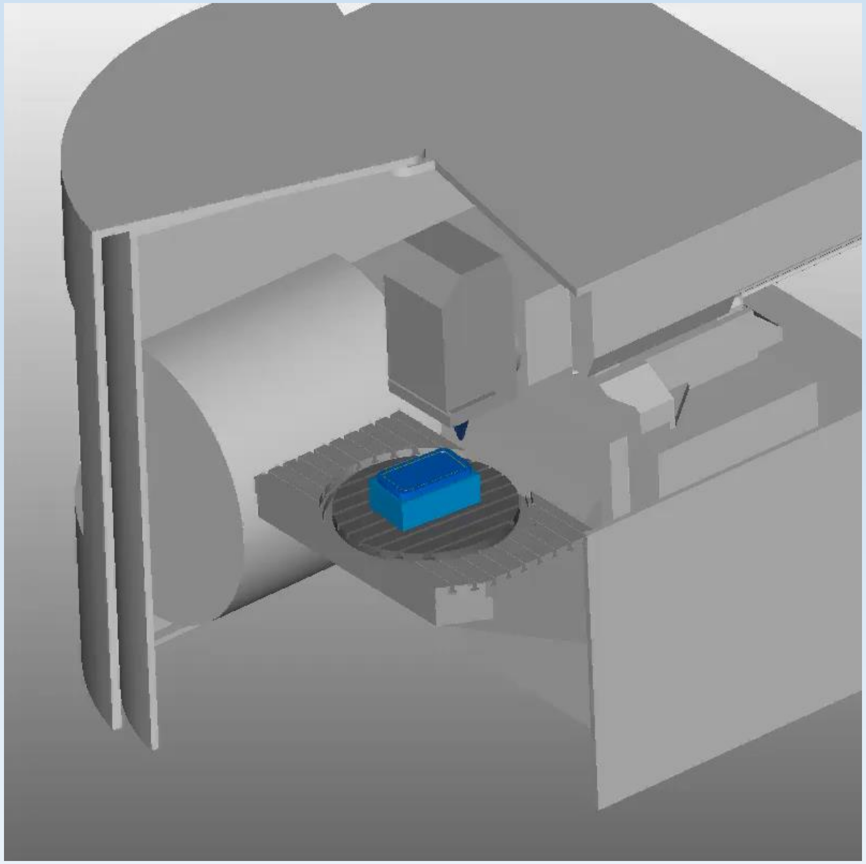


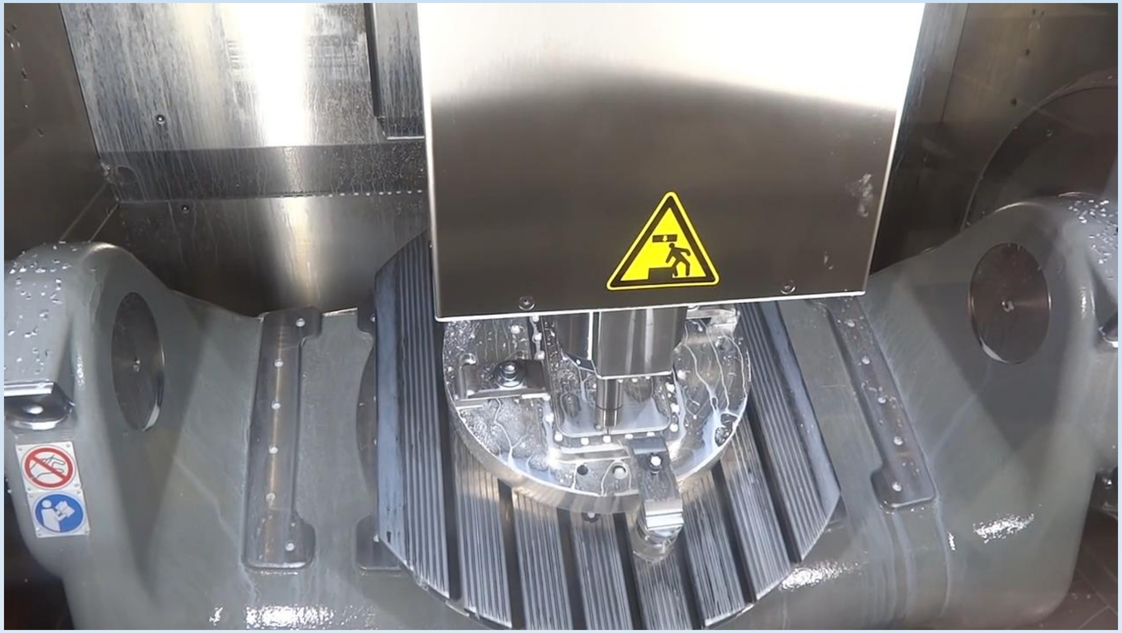






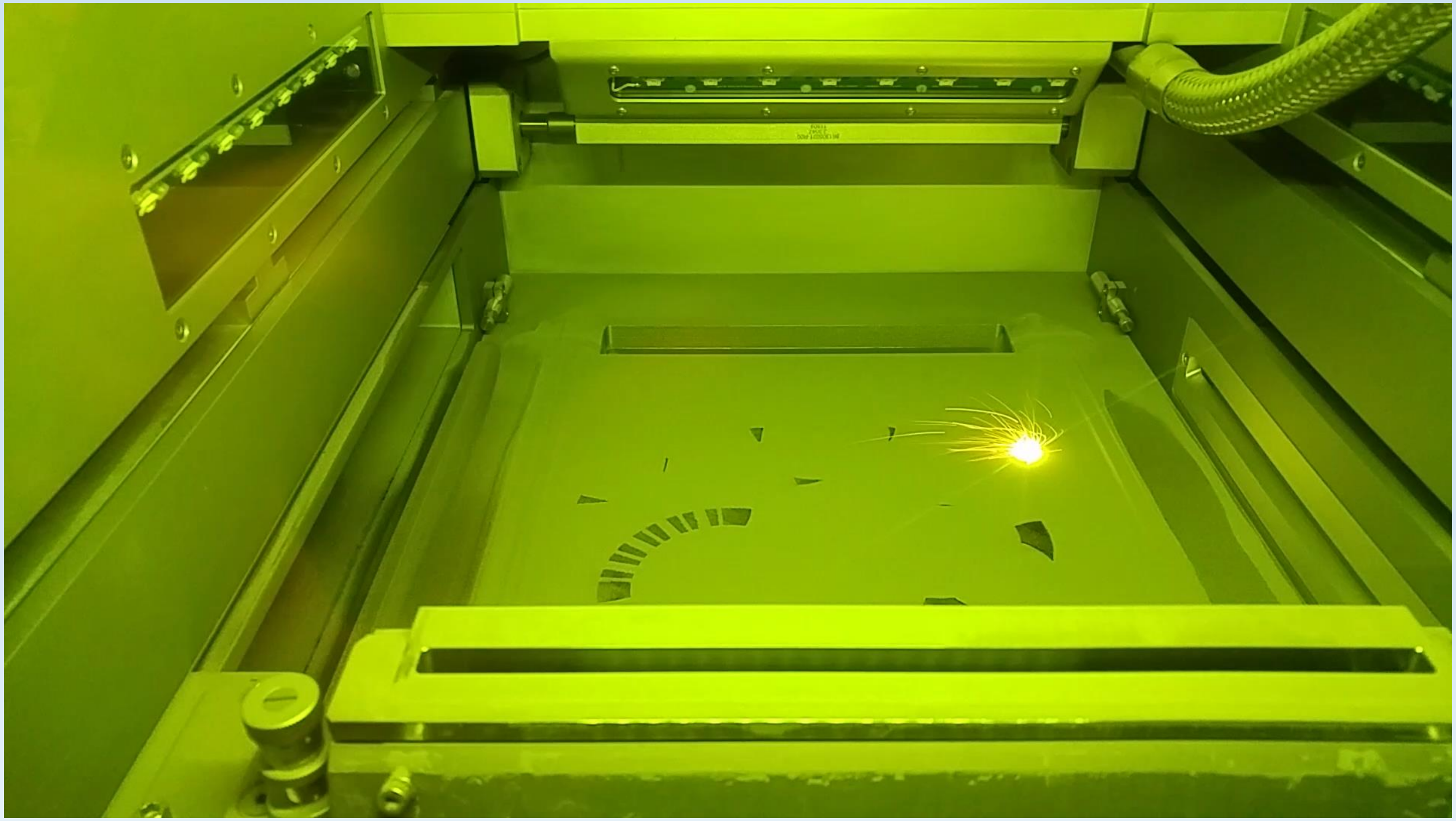
° CAM (Computer-Aided Manufacturing):

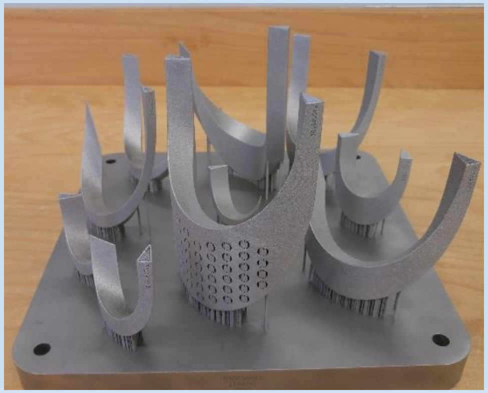




Rectangular flange – knife profile

° Metal Additive Manufacturing:



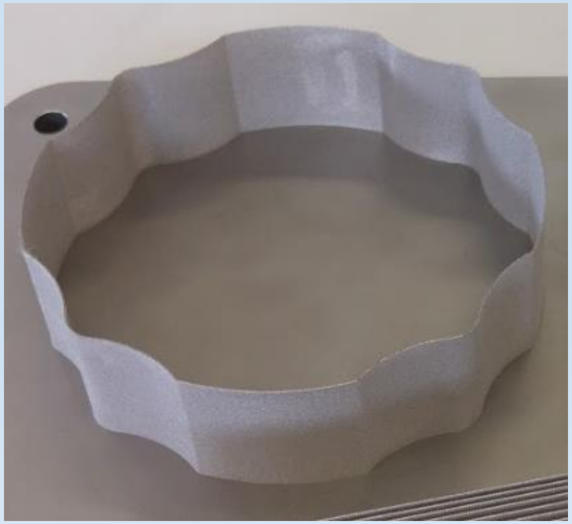


(Contact: Romain Gérard (EN/MME))

° Metal Additive Manufacturing:

Beam Screen FCC
TE-VSC

Ti_6Al_4V spring HL-LHC
TE-VSC

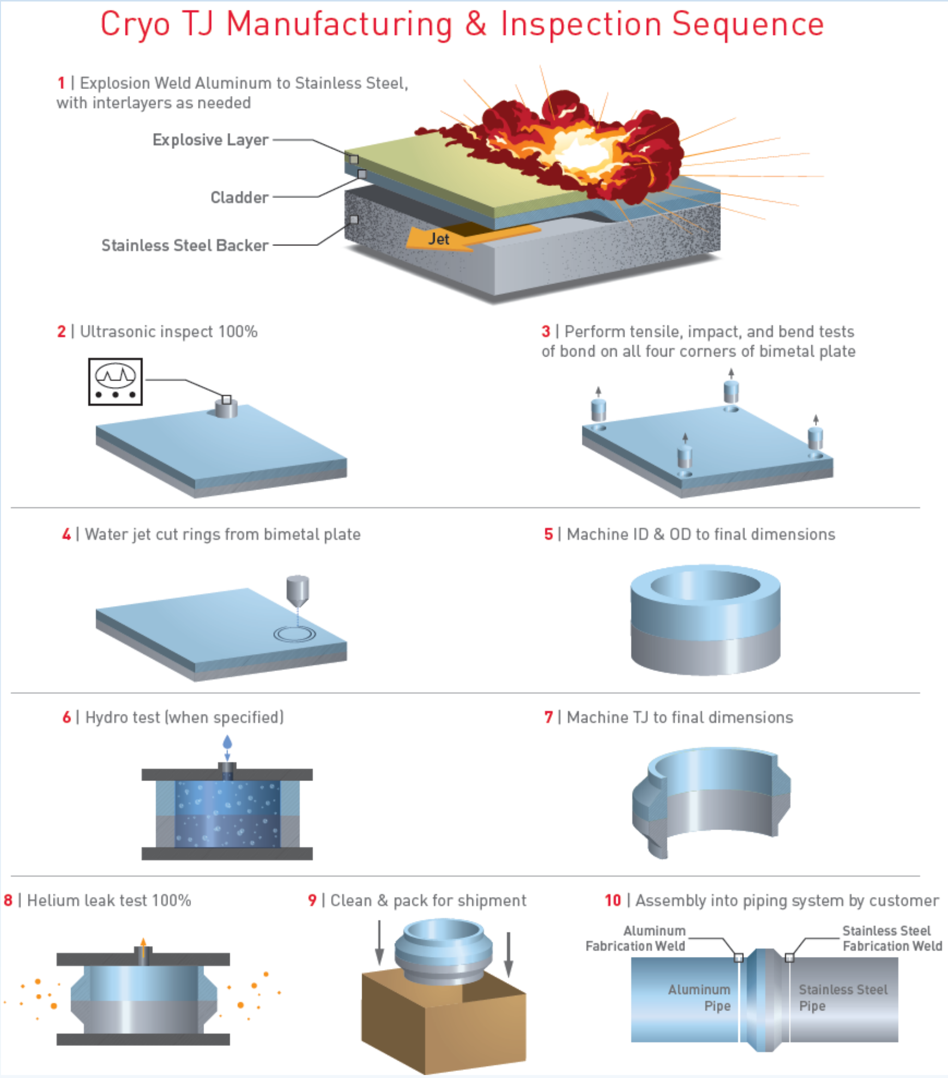


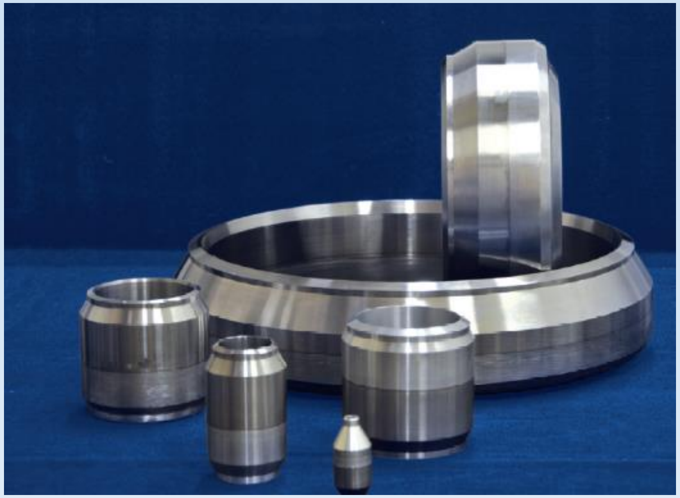
Ti_6Al_4V Flexible ring HL LHC
TE-VSC

° Qualification for UHV is still in progress (degassing, porosities, …)

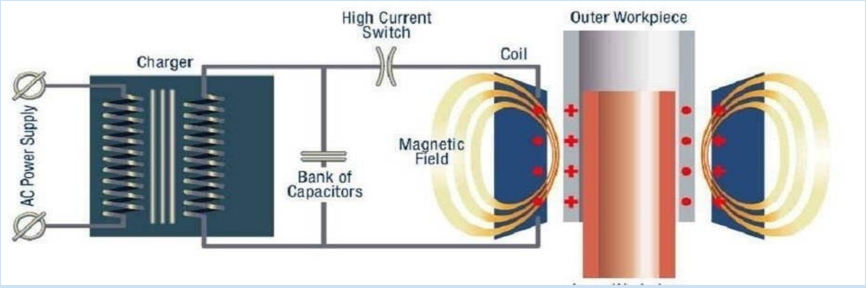
(Contact: Romain Gérard (EN/MME))

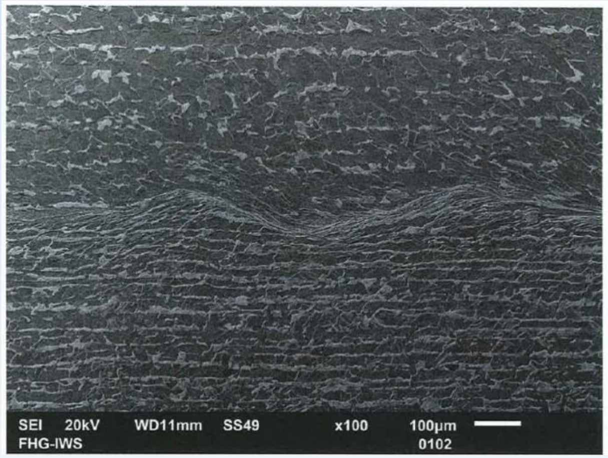
- Explosion welding:

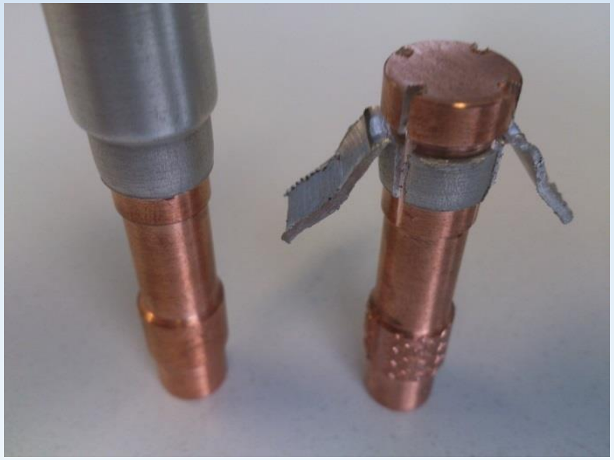




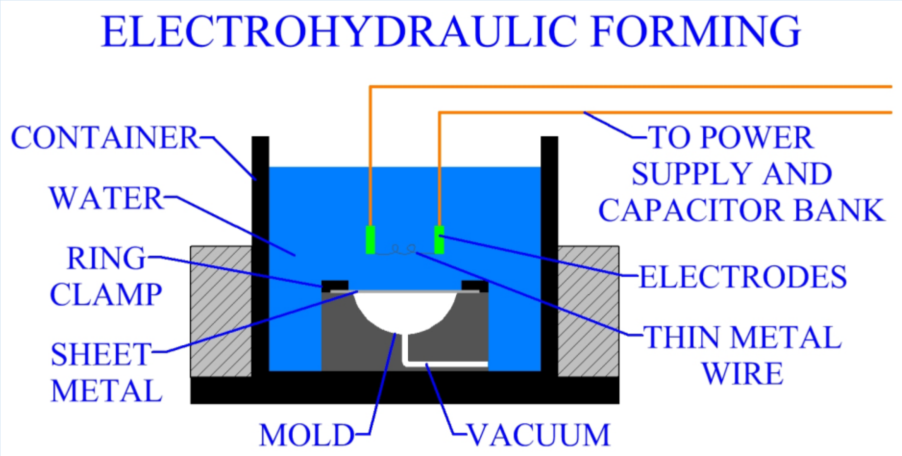
° Magnetic Pulse Welding:

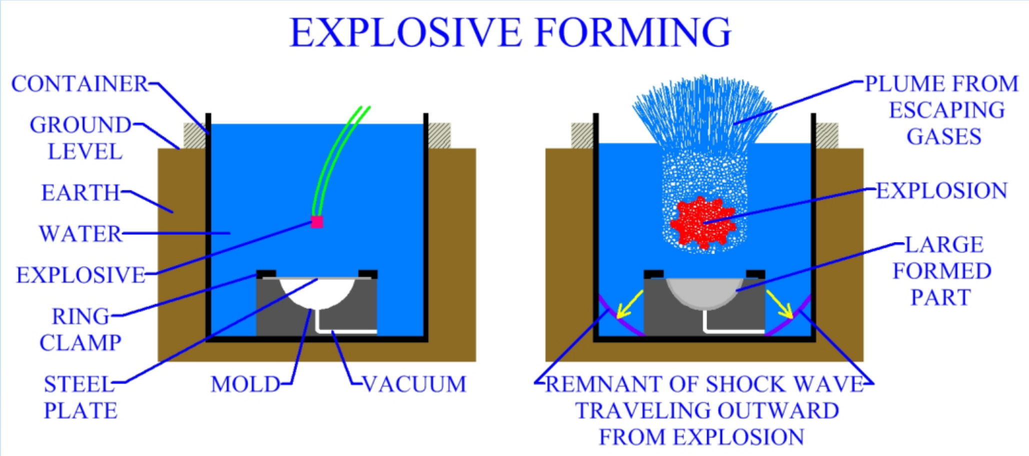






° High-velocity forming:





→ Application to Copper and Niobium for superconducting RF cavities (ex. CRAB).

° Advantages:
- Geometrical precision (≈ 150 µm instead of 600-800 µm for deep drawing or spinning).
- Increased metal formability.
- Better surface finishing.
- High reproducibility.
- Reduced cost and time for forming and post-processing.
- Economic for large series production.

Final remarks - comments

° High vacuum component manufacturing needs High quality materials!

(The majority of leaks observed on welds are due to problems with the base materials)

° The manufacturing process in defined by the design, the design must be defined by the optimum available manufacturing process.

WELDS MUST BE CARRIED OUT WITH ARGON PROTECTION WITHOUT FILLER METAL AND WITH 100% PENETRATION
WELDS MUST NOT BE GROUND OR FINISHED BY MECHANICAL ABRASION
A LEAK RATE MORE THAN 10^{-11} Pa m^3 s^{-1} (10^{-10} mbar l s^{-1}) IS UNNACCEPTABLE

° Welding process and welders must be quali

° Braze and solder alloys must be of high pur

° The welding design must avoid virtual leak (trapped volume).

° Quality inspection of the weld

Vacuum 005/2008 — Guidelines for UHV components

1.3 UHV-compatible Design

- Choose designs which:
  - avoid virtual leaks (see also Annex A),
  - allow easy cleaning (e.g. avoid inaccessible volumes). This is of particular impor component has to be particle-free (see paragraph 3).
- It is not allowed to use brazed or welded joints to separate UHV from water.

° Cutting fluid must be tested an

° Some techniques must be avoi

° Welding = distortion = geomet

° Brazing involves a heat treatm

- The mechanical p
- The grain size can increase (Copper with thin thickness!)
- Avoid brazing after (electron beam) welding.

° Some "rules" can be discussed:

- TIG without filler metal.
- Brazing grooves and virtual leaks.
- Brazing joint between vacuum and water.