진공 재료
(종류, 특성, 제작)

박종도
포항가속기연구소

사단법인 한국진공학회
The Korea Vacuum Society

진공재료 선택

재료 선택시 고려할 내용

- 얻고자 하는 진공도는?

관련 항목

- 적절한 기체방출률
  - ✓ 전처리 필요여부
- 고유 증기압
- 적절한 녹는점과 끓는점
- 재료의 누출률
- 적절한 투과율
- 불순물 기체 함유량
- 깨끗한 표면

진공재료 선택

재료 선택시 고려할 내용	관련 항목
• 강도는 충분한가?	• 1 기압차 유지 ✓허용 응력과 허용 변형
• 제작은 용이한가?	• 기계가공성, 성형성 • 적절한 접합법
• 기밀방법은? • 사용환경과 수명은?	• 금속 또는 엘라스토머 • 내부식성(내화학성) • 내방사성 • 열변형(적절한 열팽창 거동)

진공재료 선택

재료 선택시 고려할 내용	관련 항목
• 사용온도와 수명은?	• 금속 재료 또는 플라스틱? • 극저온 또는 고온? • 높은 내열피로성
• 투자율은? • 전기전도도는? • 제작 비용은?	• 전자기 특성에 영향 • 전도체 또는 부도체
• 재료 수급성은?	• 국내 또는 국외 수입 • 구입 기간

2014. 2. 진공기술강좌

Vacuum Materials

Steels

Stainless Steel

Aluminum (alloy)

Copper (alloy)

Other metals

Ceramics

Plastics

Steels

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Steels

- Mild/structural steels
  - ✓ Carbon ~ 0.2 %
  - ✓ higher outgassing rate
    - q > (20~200)x Stainless steels
    - HV compatible (10^{-6} mbar)
    - Contains contaminants of C, P, S etc.
    - endless emission of CO
  - ✓ Weldable
  - ✓ Easy to corrode
    - ✓ Needs anti-corroding coating
  - ✓ Magnetic
    - ✓ Shielding material for magnetic field

Steels

- Mild/structural steels
  - ✓ S235, S355, S20C
  - ✓ HV compatible
    - plate, pipe, rod
    - ~ 10^{-7} mbar
    - $5x10^{-10}$ (mbar l/scm^2) after bake
  - ✓ MV, RV compatible
    - Cast parts; pump and valve housing
    - ~ 10^{-3} mbar

Steels

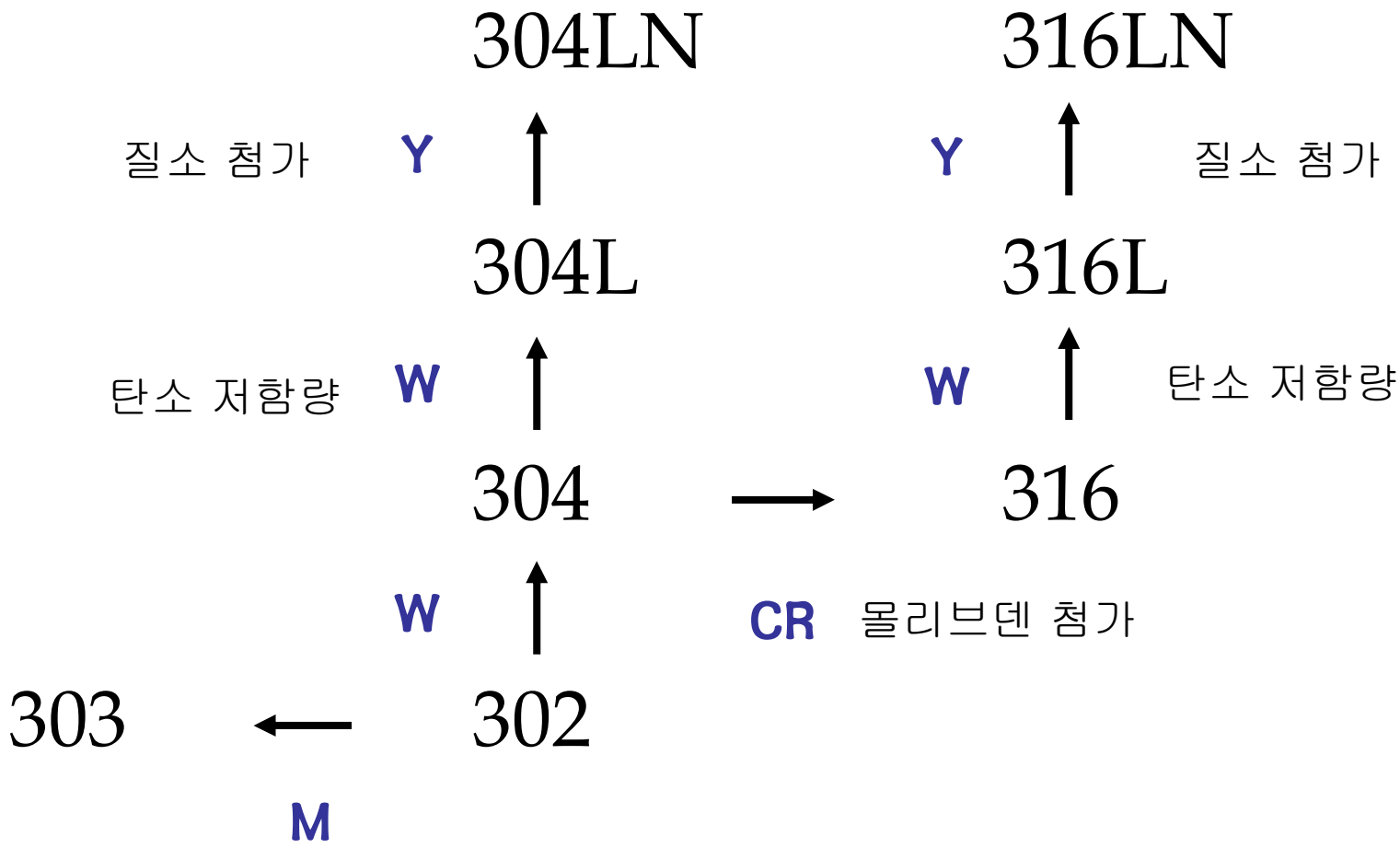
- Anti-corrosion
  - ✓ ~300°C
  - ✓ Process
- Low outgassing
  - UHV
  - XHV

Stainless steels

Stainless steel

- AISI 304/316
  - ✓ Austenitic
    - High strength
    - Non-magnetic (but, not entirely)
    - Good weldability
  - ✓ Corrosion resistance
    - During vacuum processing and bakeout (~ 300^{o}C)
  - ✓ UHV/XHV compatible
    - plate, pipe, rod
    - ~ 10^{-11} / < 10^{-12} < mbar
    - (2~6) x10^{-12} (mbar l/scm^2) after bake
    - < 1x10^{-13} (mbar l/scm^2) after special treatment

Stainless steel



18-8 Steel Family

Stainless steel

- Role of ingredients
  - Cr(10%) Resistance to oxidation
  - Ni(8%) Austenitic structure / Anticorrosion
  - Mo Accelerates passivating film formation
  - W Mechanical resistance at high temperature
  - Ti During welding and cycles stabilizes the austenitic structure
  - N Mechanical characteristics

Stainless steel

- 303
  - ✓ 19% Cr, 10% Ni, 0.15% C, 0.15% S
  - ✓ A free machining stainless.
  - ✓ Not suitable for UHV applications
    - ✓ Emission of sulfur at higher temperature
    - ✓ (The outgassing rate of 303 stainless can be lowered to 10^{-13} mbarl/sec cm^2 by a combination of fabrication and post treatments such as bakeout.)
  - ✓ Welding for vacuum systems is a problem due to the evolution of sulfur during welding causing porosity.

Stainless steel

- 304
  - ✓18% Cr, 8% Ni, 0.08% C
  - ✓Most common materials used in vacuum technology
  - ✓Less carbide precipitation
  - ✓Cleaner machining and better welds than 304
- 304L
  - ✓18% Cr, 8% Ni, 0.03% C
  - ✓One of common steels used in vacuum technology
  - ✓Less carbide precipitation
  - ✓Cleaner machining and better welds than 304

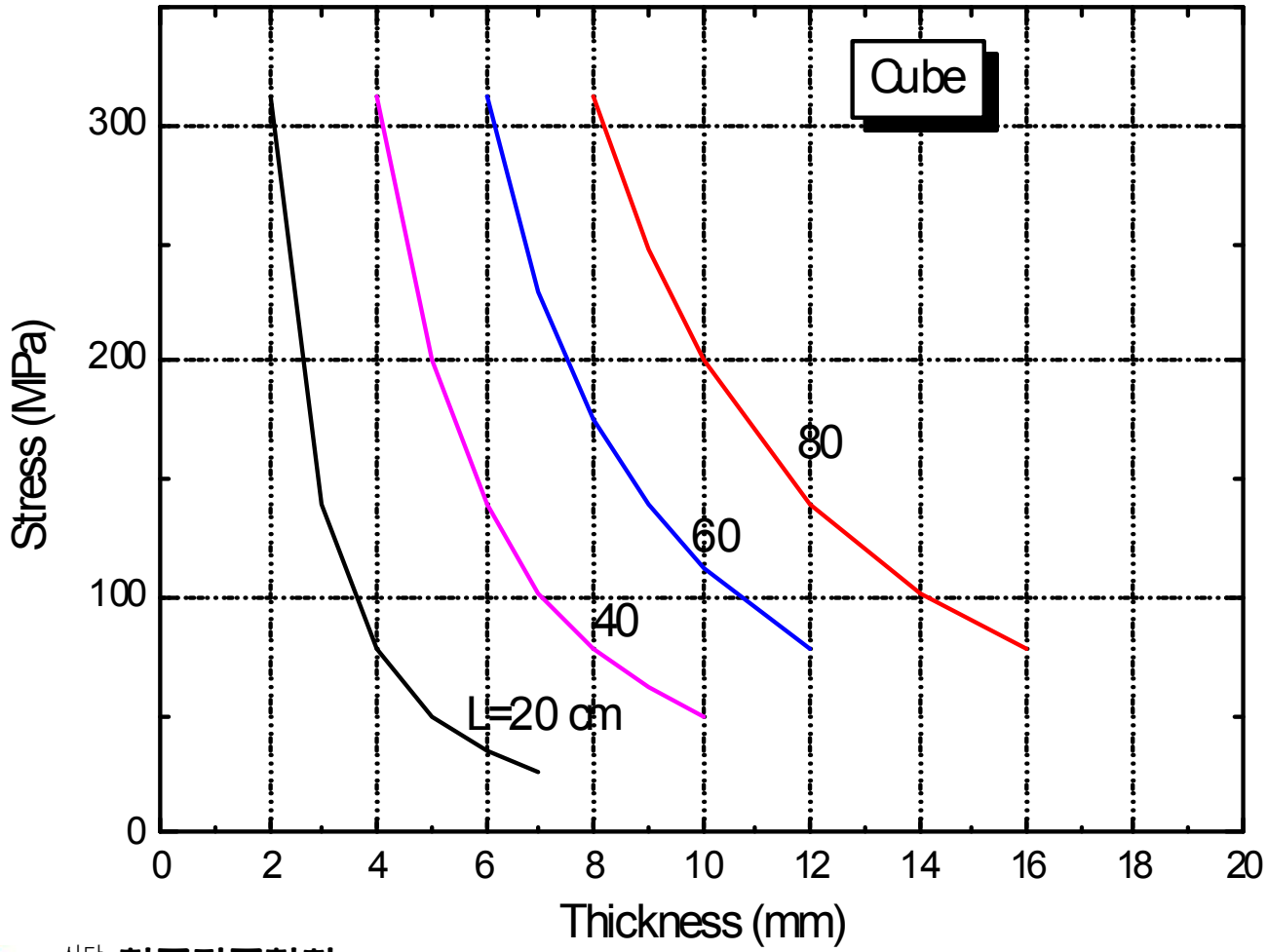
Stainless steel

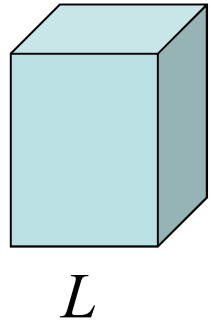
- 316L
  - ✓ 18% Cr, 14% Ni, 0.03% C, 3% Mo
  - ✓ Stabilized with molybdenum to prevent carbide precipitation in the weld zone
  - ✓ Lower outgassing rates than 304(L)
    - ~2 x10^{-12} (mbar l/scm^2) after bake
    - < 5x10^{-14} (mbar l/scm^2) after special treatments
  - ✓ Used where chemical compatibility is a concern.
  - ✓ Low-magnetic stainless steels (μ_r< 1.02)
    - Suitable for analyzers, accelerators
      - Heat treatment; (750 ~ 1050^{o}C)

Mechanical properties

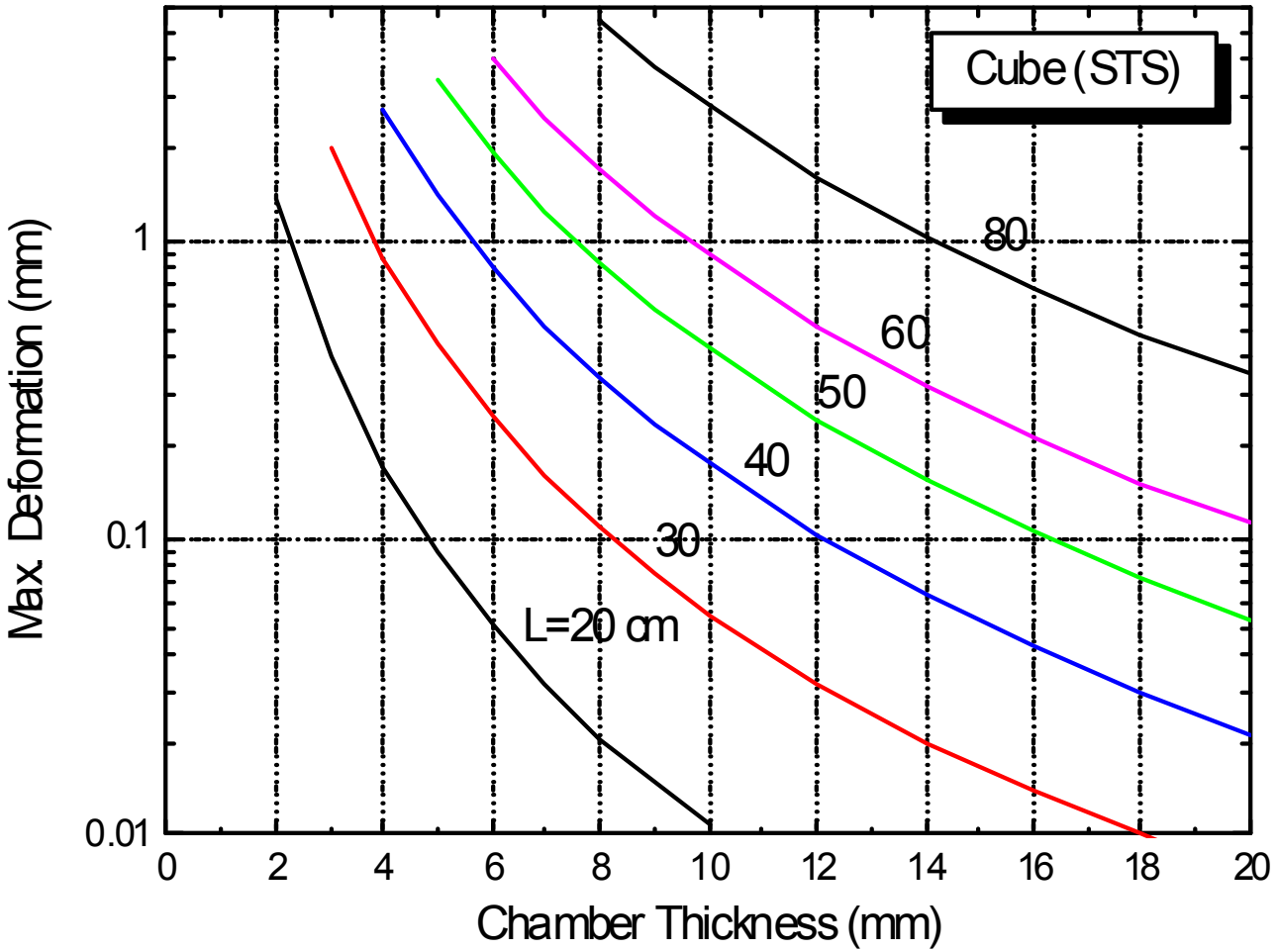
	Yield strength (항복강도,내력,내구력)		Tensile strength (인장강도)	
	Kgf/mm^2	MPa	Kgf/mm^2	MPa
304, 316	21	205.8	53	519.4
304L, 316L	18	176.4	49	480.2
A5083	7.24	71.0		
A6061,6063	7.03	68.9		

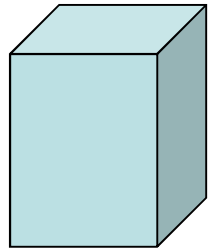
Stress : Cube


Cube
Stress (MPa)
Thickness (mm)
0
100
200
300
0
2
4
6
8
10
12
14
16
18
20
80
60
40
L=20 cm

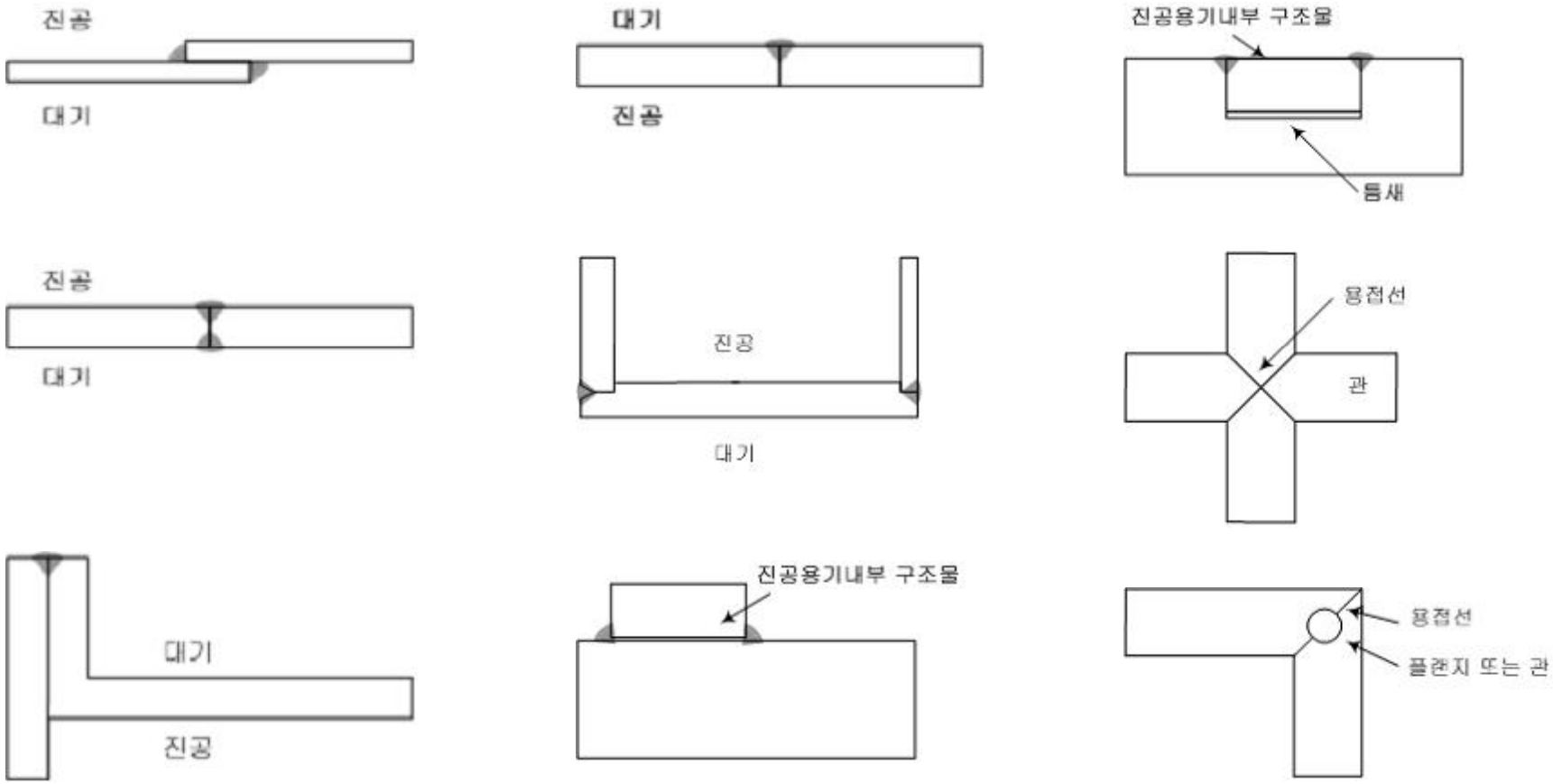

L

Deformation : Stainless steel





피해야 하는 용접



→ "초고진공 용접핸드북(KRISS)"

Aluminum (alloys)

Aluminum (alloys)

- 1xxx pure aluminum
  - ✓ > 99% Al by weight
  - ✓ A1050; suitable for metal gaskets
  - ✓ can be work hardened
- 2xxx copper alloys
  - ✓ can be precipitation hardened
  - ✓ Duralumin; once the most common aerospace alloys (they were susceptible to stress corrosion cracking and are increasingly replaced by 7000 series in new designs.)
  - ✓ A2219; suitable for Conflat flange (weldable)

Aluminum (alloys)

- 3xxx manganese alloys
  - ✓ can be work hardened.
  - ✓ A3004; suitable for vacuum bellows

- 4xxx silicon alloys
  - ✓ known as Silumin

Aluminum (alloys)

- 5xxx magnesium alloys
  - ✓ easy to machine, higher strength, good weldibility
  - ✓ A5083; used in accelerators

- 6xxx magnesium and silicon alloys
  - ✓ Easy to machine
  - ✓ can be precipitation hardened
    (but not to the high strengths that 2xxx and 7xxx can reach)
  - ✓ A6063; most common materials in vacuum technology
  - ✓ A6061; one of the most vacuum materials

Aluminum (alloys)

- 7xxx zinc alloys
  - ✓ with can be precipitation hardened
    (to the highest strengths of any aluminum alloy)

- 8xxx lithium alloys

Aluminum (alloys)(진공용)

재 료	처 리	주요 합금성분 (%)		용 도
2219	T87, T852	Cu 5.8-6.8	Mn 0.2-0.4	플랜지
3004		Mn 1-1.5	Fe 0.25	벨로우즈
5052		Mg 2.2-2.8	Fe 0.4	진공용기, 벨로우즈
5083	H321	Mg 4-4.9	Mn 0.4-1	진공용기
6061	T5, T6	Mg 0.8-1.2	Si 0.4-0.8	진공용기, 벨로우즈
6063	T5, T6	Mg 0.45-0.9	Si 0.2-0.6	진공용기
6263		Mg	Si	진공부품 (티, 크로스,엘보)
6951	T6	Mg 0.4-0.8	Si 0.2-0.5	벨로우즈

Temper designation

- -F As fabricated
- -H Strain hardened (cold worked) with or without thermal treatment
  - -H1 Strain hardened without thermal treatment
  - -H2 Strain hardened and partially annealed
  - -H3 Strain hardened and stabilized by low temperature heating
- Second digit A second digit denotes the degree of hardness
  - -HX2 = 1/4 hard
  - -HX4 = 1/2 hard
  - -HX6 = 3/4 hard
  - -HX8 = full hard
  - -HX9 = extra hard
- -O Full soft (annealed)

- -T Heat treated to produce stable tempers
  - -T1 Cooled from hot working and naturally aged (at room temperature)
  - -T2 Cooled from hot working, cold-worked, and naturally aged
  - -T3 Solution heat treated and cold worked
  - -T4 Solution heat treated and naturally aged
  - -T5 Cooled from hot working and artificially aged (at elevated temperature)
  - -T51 Stress relieved by stretching
  - -T510 No further straightening after stretching
  - -T511 Minor straightening after stretching
  - -T52 Stress relieved by thermal treatment
  - -T6 Solution heat treated and artificially aged
  - -T7 Solution heat treated and stabilized
  - -T8 Solution heat treated, cold worked, and artificially aged
  - -T9 Solution heat treated, artificially aged, and cold worked
  - -T10 Cooled from hot working, cold-worked, and artificially aged
- -W Solution heat treated only.

Aluminum (alloys)

- A6063-T5(T6)
  - ✓ The most widely used aluminum alloy
  - ✓ The most common materials in vacuum technology
  - ✓ Low outgassing rates
    - $< 5x10^{-12}$ (mbar l/scm^2) after bake at 150^{o}C
  - ✓ Easy to forming using *extrusion*, machining and welding
  - ✓ Alloy retains its strength after welding
  - ✓ ConFlat® flanges are made from A2219 with knife edge coated with TiC (TiN, CrN).
    - ✓ With A1050 metal gaskets

- Mainly used in UHV and forelines
- Bakoout temperature
  - Max 180^{o}C
  - In-general 100 – 150^{o}C
- Melting point; 660^{o}C (P_{vapor}=10^{-8} mbar)
- Entirely non-magnetic
- High thermal and electrical conductivity

Aluminum (alloys)

- A6061-T5(T6)
  - ✓ The most widely used aluminum alloy
  - ✓ Low outgassing rates
    - ✓ < 5×10^{-12} (mbar l/scm^2) after bake at 150^{o}C
  - ✓ Easy to forming using *machining* and welding
  - ✓ Alloy retains its strength after welding
  - ✓ ConFlat® flanges are made from A2219 with knife edge coated with TiC (TiN, CrN).
  - ✓ Large chambers which would be difficult to heat treat in to T6 condition are often made from 5083.

Aluminum (alloys)

- Initial outgassing rate is higher(~ 5x) than that of SST.
  - ✓ The desorption rate of water vapor from the surface of aluminum is slower than stainless steels which gives it different initial pump down characteristics.
- Anodizing
  - ✓ a common surface treatment.
  - ✓ produces hard inert surface, but outgassing rate is degraded by ~x10.
  - ✓ Not suitable for UHV applications

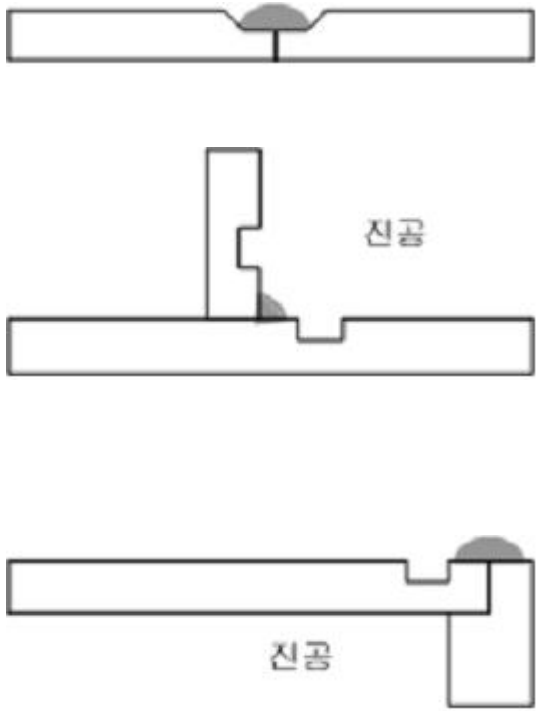
✓ Suface oxidation

- ✓ Suitable for UHV and XHV applications

알루미늄 용접

- Al alloys require special attention to both weld design and weld technique.

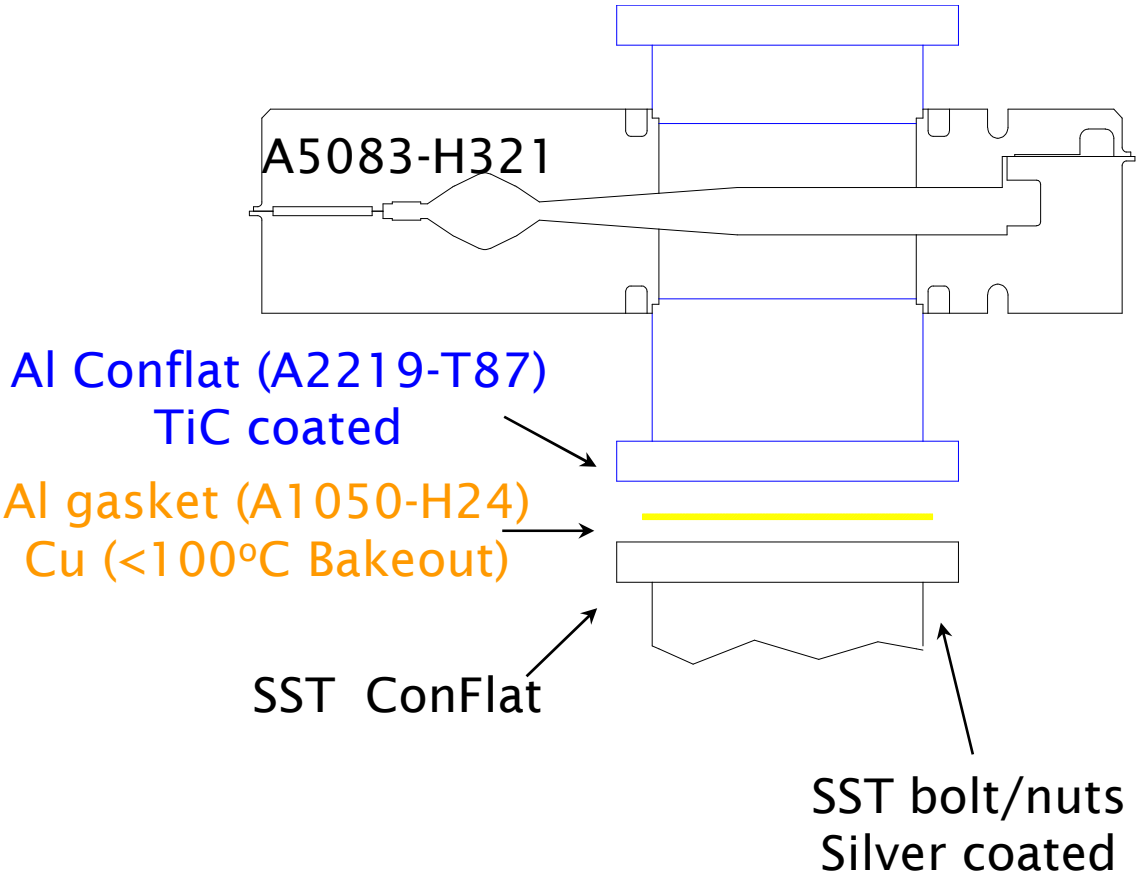
ac-TIG welding
(with filler metal)



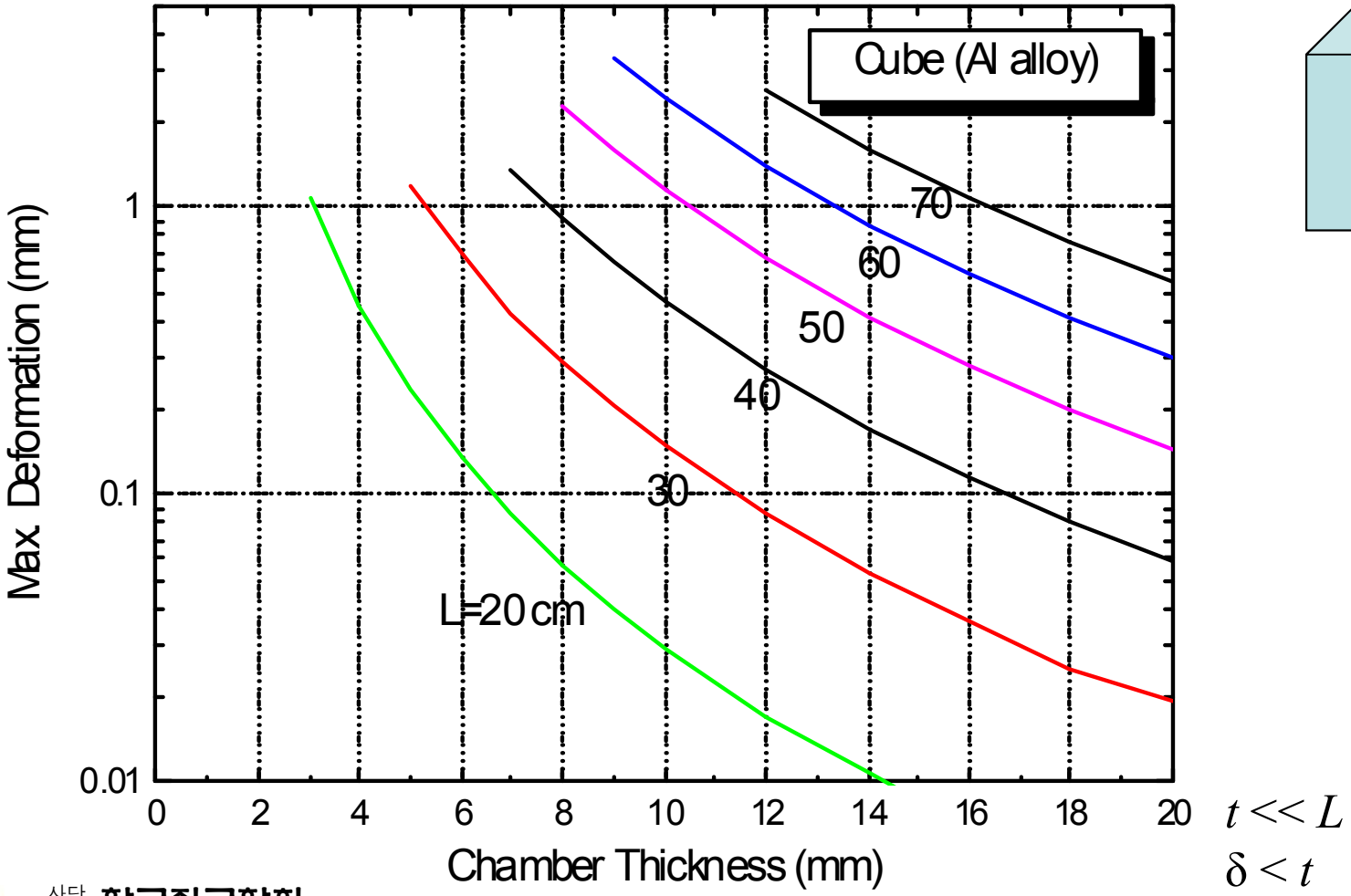
→ "초고진공 용접핸드북 (KRISS)"

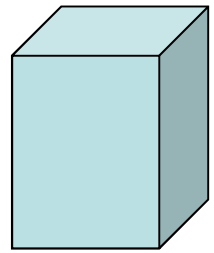
Vacuum Seals

- Al/SST hybrid ConFlat system



Deformation : Al alloy





$t << L$

$\delta < t$

SST – Al 비교

		Stainless steel	Aluminum alloy
Vacuum characteristics	Outgassing rate	depends on surface treatments	
	Preinstallation bakeout	950℃	< 210℃
	In situ bakeout	150 - 450℃	< 150℃
Mechanical characteristics	Mechanical strength	higher (×1.5)	
	Thermal expansion coefficient		higher (×2)
	Thermal conductivity		higher (×15)
	Shaping by machining		easier
	Shaping by extrusion		easier
	Shaping by welding	easier	
	Quality of demountable seals	better	
Other characteristics	Magnetic property	not entirely non-magnetic	completely non-magnetic
	Residual radioactivity		lower

Copper (alloys)

Copper (alloy)

- High thermal and electrical conductivity
  - Suitable for electrical feedthrough
  - Suitable for thermal/radiation absorber
  - Suitable for cryogenic applications
- Hydrogen embrittlement
  - For HV and UHV, coppers(alloys) with oxygen free or reduced oxygen contents are required.
- Bakout; Up to 300^{o}C in vacuum
- Cold welding; OHFC gasket for ConFlat flanges
- Joining techniques; brazing, soldering, welding
- Outgassing rate; ~ 10^{-9} mbar liter/sec cm^{2}

Copper alloy

Brass and Tombac

- Tin or Zinc alloys
  - High vapor pressure at high temperatures
    (Used in vacuum systems where temperatures above 100°C are n ot found)
  - Easy to machine
  - Cheap
- Commonly used in rough and high vacuum chambers a nd fixtures.
- Common joining techniques: Soldering
- Outgassing rate
  ~ 10^{-7} mbar liter/sec cm^2

Copper alloy

- To increase its strength
  - OFC + Al_2O_3(0.1-0.5%) GlidCop
    - Yield strength(at 0.2% offset) > 200 Mpa (OFC ~ 100 MPa)
  - OFC + Ag or $Au_{0.2\%}$ Expensive (x 4)
  - OFC + Zr High outgassing rate

Outgassing rates

Q(Torrl/scm^2)	@ 10 hour	Baked
Aluminum	$5x10^{-8}$	$5x10^{-13}$
Aluminum (anodized)	$3x10^{-7}$	$5x10^{-10}$
Stainless steel	$1x10^{-8}$	$2x10^{-12}$
Mild Steel	$2x10^{-7}$	$5x10^{-10}$
1018 Steel (Ni plated)	$5x10^{-7}$	
Brass	$6x10^{-7}$	
Copper	$5x10^{-9}$	$1x10^{-12}$
Copper (OFHC)	$2x10^{-9}$	$1x10^{-12}$

Other metals

Gold and Silver

- Gold
  - ✓ Very low vapor pressure
  - ✓ Used as metal gaskets, surface seals in valves
    as coating for electrical conductors
  - ✓ Used as brazing filler alloys
    - ✓ Cu/Au or Cu/Au/Pd
- Silver
  - ✓ Very low vapor pressure
  - ✓ Silver plated bolts/nuts to reduce friction/cold weld.
  - ✓ High oxygen permeation rate through silver at high temperature.

Titanium

- Very active metal
- Easily react with O_2, N_2 at > 150°C
  - ✓ Weld should be done with inert gas environment
- Used as metalizing materials for brazing
- TSP(Titium sublimation pump)
  - ✓ Sublimation at ~ 1,350°C
  - ✓ ~ 5 um coating for 1 hr
  - ✓ High oxygen permeation rate through silver at high temperature.
- Ion pump
  - ✓ Cathode material

Indium

- Melting point; 156°C
  - Not suitable for bakeable UHV applications
- Very low vapor pressure
- Very soft
- High thermal conductivity

- Thus indium may be used as
  - ✓ vacuum seal for UHV at cryogenic applications
  - ✓ thermal conductors between two different metals

Ceramics

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Ceramics

- Ceramics
  - ✓ Non-metal, inorganic materials
  - ✓ Mainly used as insulators in vacuum technology
- Three types of ceramics
  - ✓ Pure-oxide ceramics
  - ✓ Silicate ceramics
  - ✓ Glass-ceramics

Ceramics

- Pure oxide ceramics
  - ✓ Alumina, Zrconia, Beryllium oxide,…
  - ✓ Alumina (Al_2O_3)
    - Mostly used ceramics
    - Max temperature; 1,800°C
    - > 92% in vacuum technology
    - Can be brazed
    - Mainly used as electrical feedthroughs
      - Balable upto 350°C
    - Tensile strength 25 kpsi (96% density)
  - ✓ Sapphire (monocrystalline Al_2O_3)
    - UV and IR transparent
    - Used as vacuum window

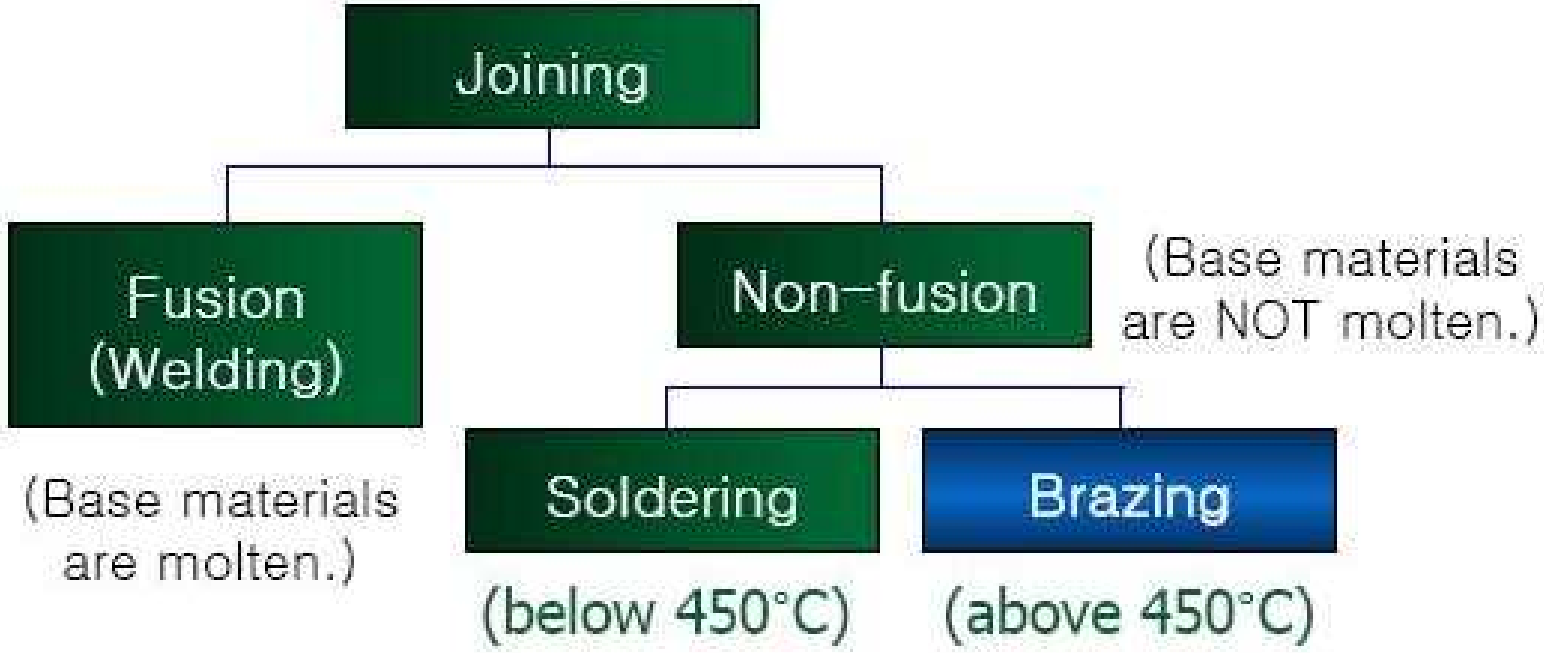
Ceramics

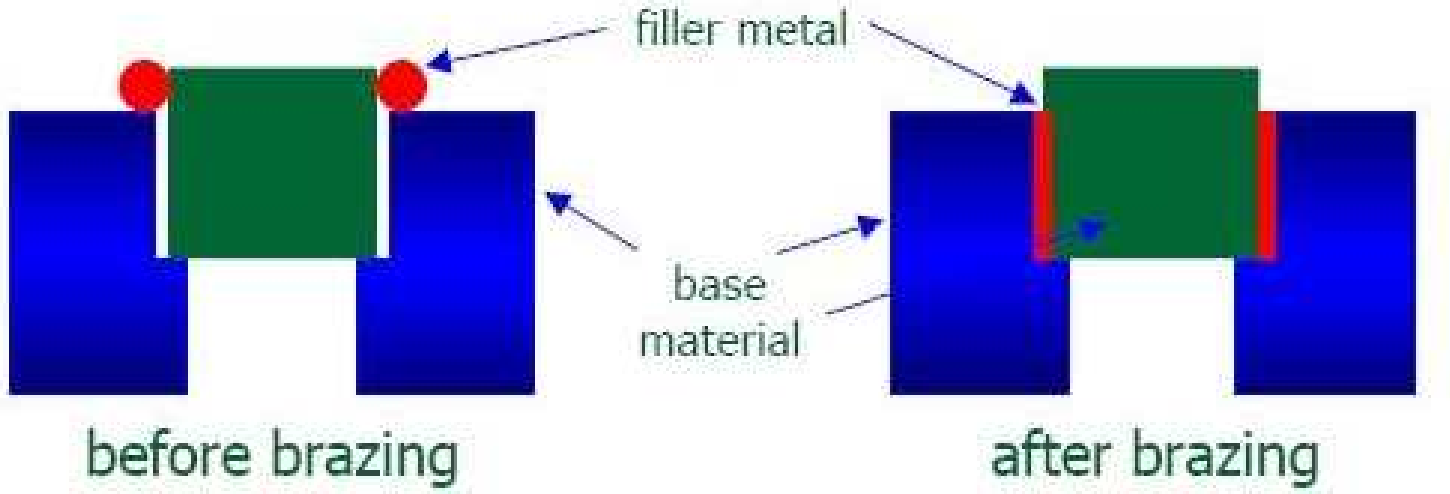
- Silicate ceramics
  - ✓ Steatite (MgO-SiO_2)
    - Max temperature 1,000°C
    - Tensile strength 15 kpsi
- Glass-ceramics
  - ✓ Crystalline ceramic
    - Can be machined with standard tools
    - Macor®, Corning 9658

Ceramics

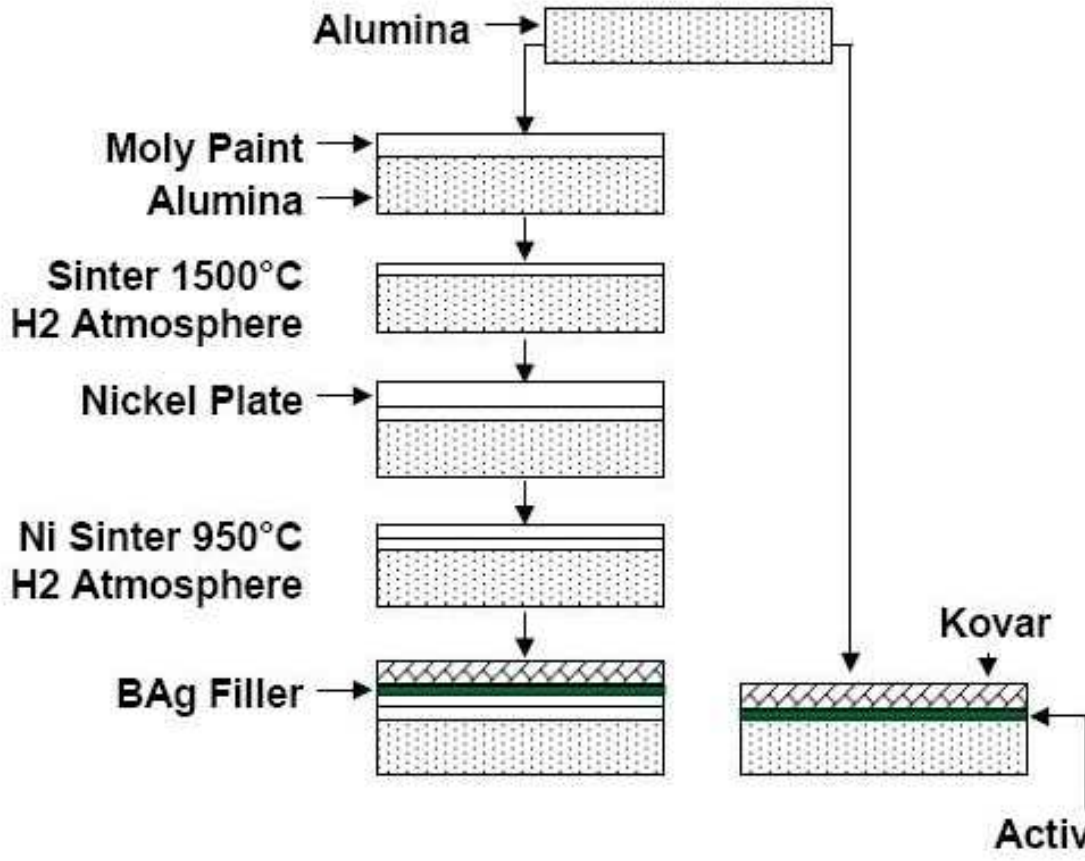
- Kovar
  - ✓ Fe-Ni-Co alloy (thermal expansion ~ glass)
  - ✓ Magnetic
  - ✓ Intermediate material between ceramic and metal for brazing joint

Permanent vacuum joints





Brazing



- Metallization Method
  - Mo/Mn Paint Sintering
  - Vapor Deposition
- Active Brazing

$Al_2O_3 + 3Ti \rightarrow 2Al + 3TiO$

- Active Soldering
  - Brushing, Vibration required
  - No Spreading

Zeolite

- Very porous alumina silicates with alkali metals
- Mainly used as drying agents
- Mostly used as vapor adsorbing agents in vacuum
- Sorption pump
  - Liquid nitrogen cooled
  - Regeneration by heating

Plastics

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Plastics

- Elastomers
  - Rubber-like materials
  - Elastic
  - Used as reusable vacuum gaskets for RV, MV, HV, or (UHV)
  - Viton, Kalez, …
- Thermoplastics
  - Thermally reversible
- Duroplastics
  - Thermally irreversible
  - Epoxy
  - Good adhesion with metals, glasses, ceramics

Outgassing rates

	Outgassing rate (Torrl/scm^2)	
	@ 10 h	Baked
Viton	$5x10^{-8}$	$5x10^{-10}$
Buna N	$2x10^{-6}$	$4x10^{-8}$
Silicon rubber	$8x10^{-7}$	$6x10^{-10}$
Epoxy (Shell Epon)	$1x10^{-6}$	$8x10^{-8}$
Teflon (poly'fluoro'lene)	$8x10^{-8}$	$8x10^{-9}$
Mylar	$1x10^{-7}$	$2x10^{-9}$
Nylon (polyamide)	$3x10^{-7}$	$6x10^{-9}$
PVC	$3x10^{-7}$	$8x10^{-8}$

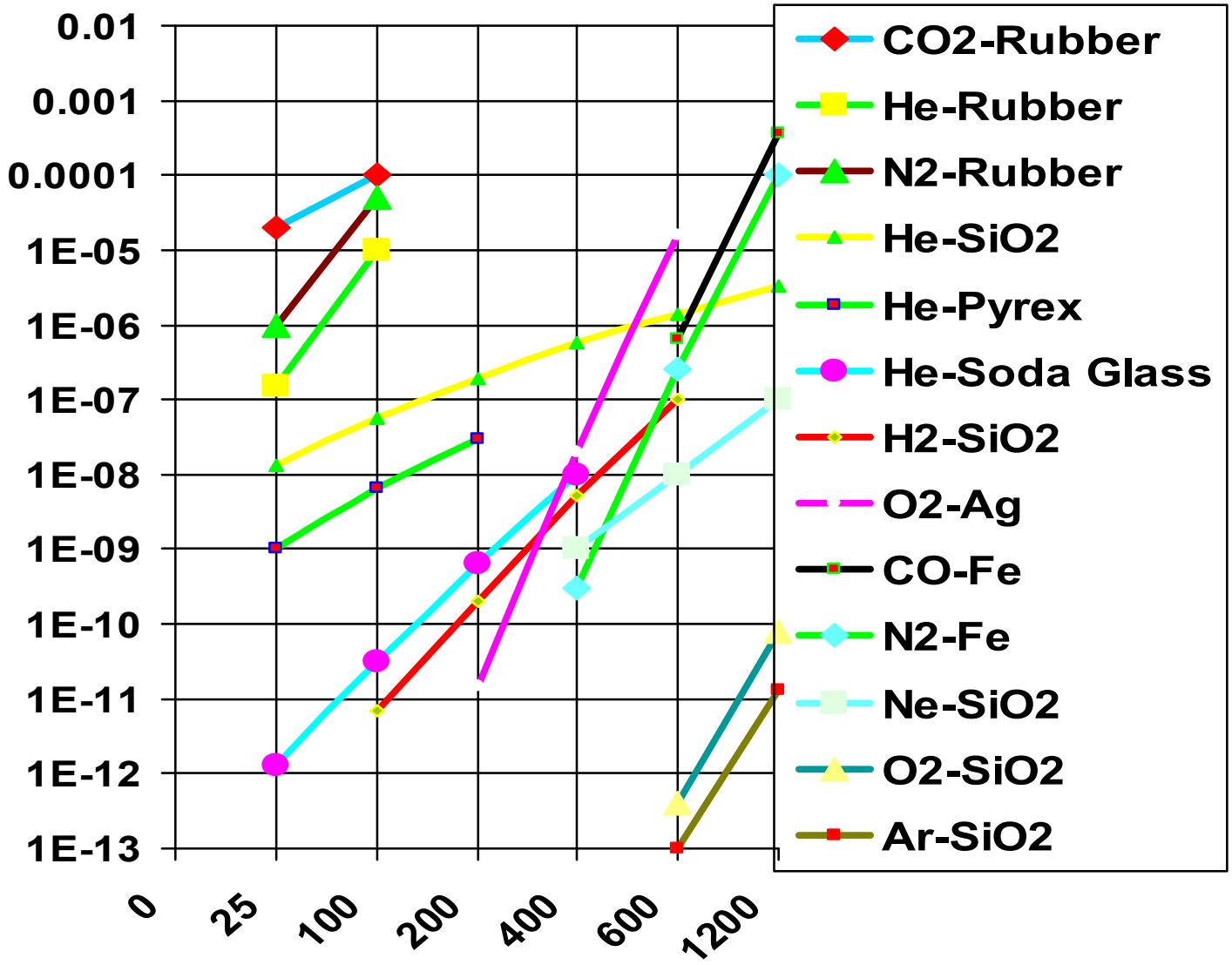
O-ring seal

Permeation

- Permeation through solid materials involves
  - sorption, diffusion and desorption.

- Materials have permeation rates for different gases specific to that material.
  - steels have higher permeation rates with higher carbon content;
  - copper has low permeation for all gases;
  - aluminum has low permeation for hydrogen;
  - silver has high permeation rate for oxygen at high temperature
  - palladium has high permeation rate for hydrogen
  - polymers are permeable to all gases.

Permeation


0.01
0.001
0.0001
1E-05
1E-06
1E-07
1E-08
1E-09
1E-10
1E-11
1E-12
1E-13
0
25
100
200
400
600
1200
CO2-Rubber
He-Rubber
N2-Rubber
He-SiO2
He-Pyrex
He-Soda Glass
H2-SiO2
O2-Ag
CO-Fe
N2-Fe
Ne-SiO2
O2-SiO2
Ar-SiO2

Permeation

- Permeation is a strong function of temperature.
- Permeation gives additional gas loads.
  - Modifies the chamber environment(residual gases)
  - effecting chemistry in vacuum process
  - Limits the ability to reach ultra high vacuum.
- Calibrated leaks
  - helium permeation through pyrex or quartz.

Helium permeation through elastomers

Polymer	Permeation rates std-cc/s cm^2 ($x10^{-7}$) at 1 atm	
	25°C	150°C
Viton	1.3	49
Buna N	0.8	25.2

After several minutes helium will begin to permeate through the elastomer O-ring and show up as a leak.