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Optimization of Condition for Invar/Stainless HIP Diffusion Bonding

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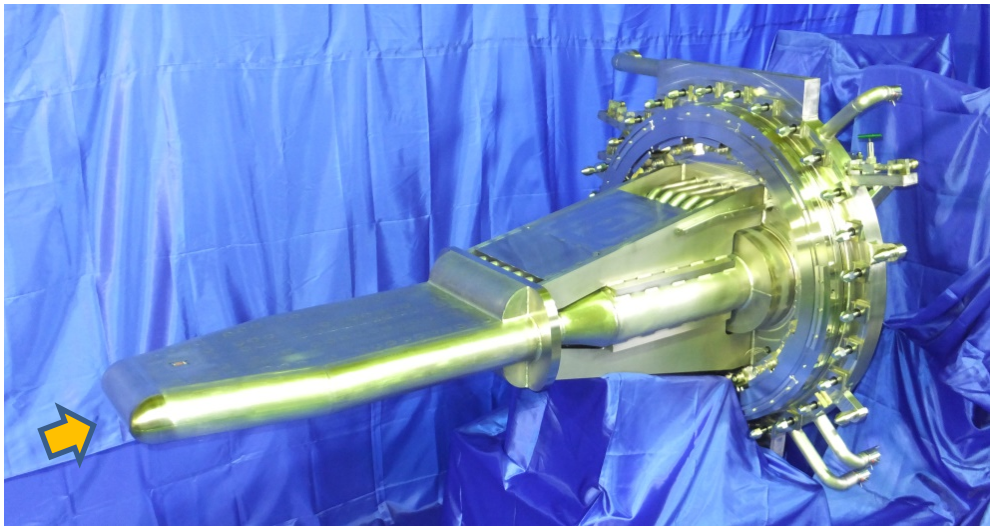
Background

Mercury target vessel for spallation neutron source in J-PARC

Proton beam



- Size : **1.3 x 1.3 x 2.5 m^3**
- Weight : 1600 kg
- Material : Type 316L stainless steel (316L SS)
- Life time : **One year** @1MW operation (Plan)
  (Radiation damage, Pitting damage)

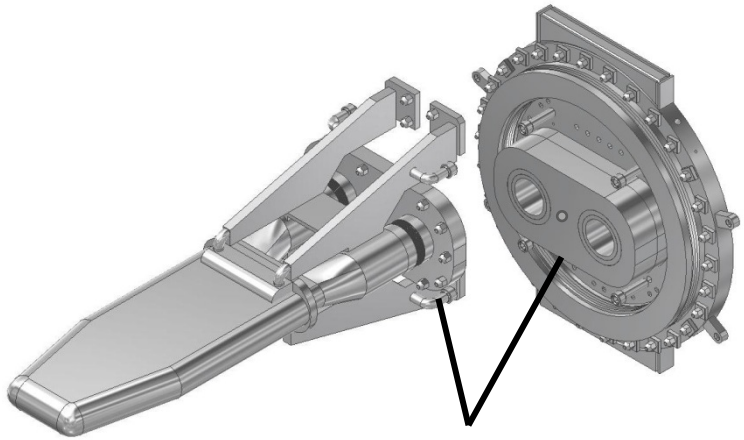
Facility operable period : **30 years** (Plan)

30 used target vessels

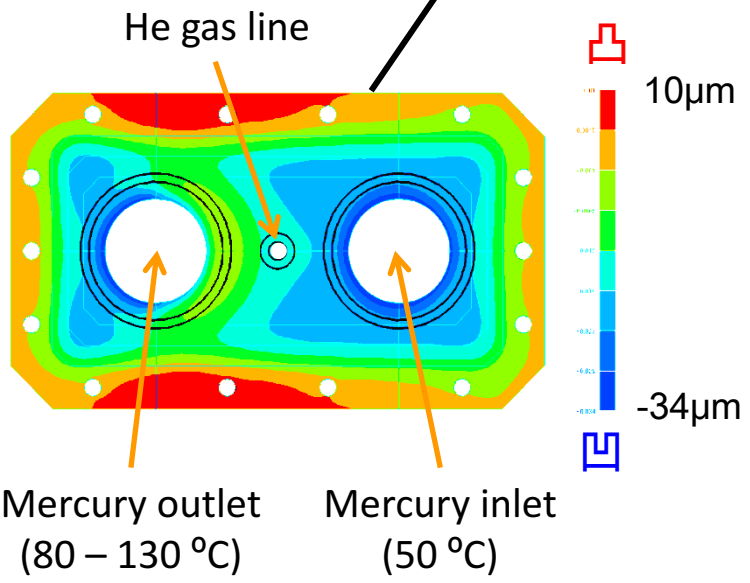
All used target vessels will be stored in J-PARC site.
But there is no space to store all of them.

Requirements of additional flange

- **Connecting with plural pipes simultaneously**
  2 mercury pipes (Design pressure: 0.5MPa)
  1 helium gas pipe (Design pressure: 0.5MPa)
- **Maximum thickness of flange**
  70 mm ← limitation of dimensional outline
- **High seal performance** for preventing release of radioactive materials
  < 1×10^{-6} Pa·m³/s (Helium gas leak test)
- **Minimum deformation of gasket due to fastening by bolts**
  0.2 mm ← 0.1 mm (Result of mockup tests) x 2
- **Maximum deformation of flange due to fastening by bolts**
  0.2 mm ← 0.3 mm (Average of gasket deformation due to fastening by bolts)
- **Maximum thermal deformation of flange during beam operation**
  8 μm ← 40 μm (Result of mockup tests) / 5



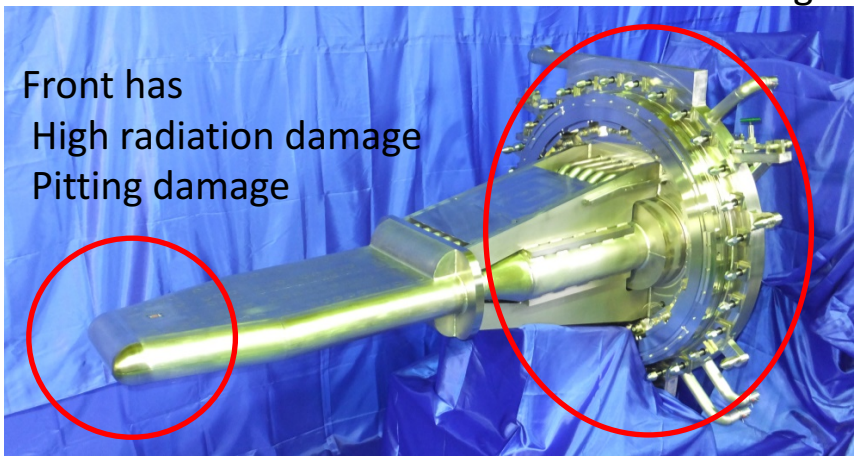
Additional flange

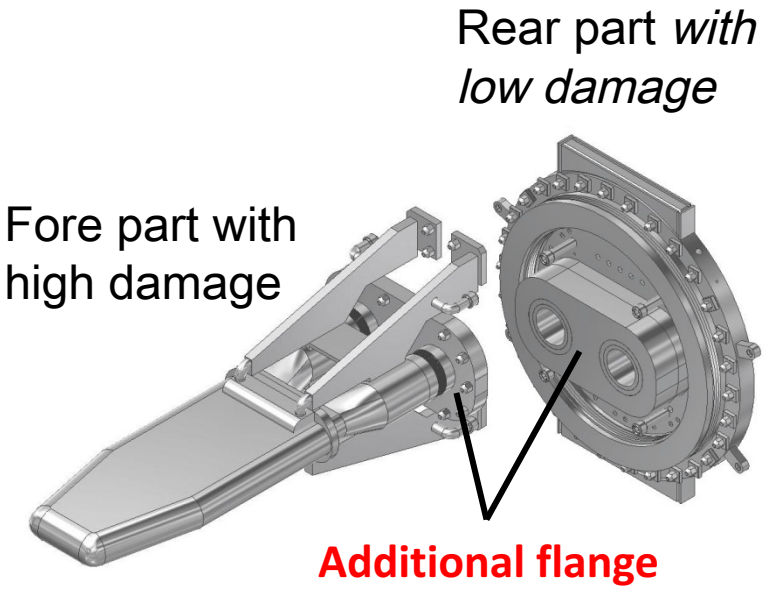


Thermal deformation distribution

Separate type target vessel

Divided structure with additional flange is applied to use low damage part repeatedly.





Conceptual diagram

Division position is defined taking into account of followings.

- Waste volume
- Thermal load relating with thermal deformation of flange
- Dimensional outline without intervention with other components
- Performance of remote handling for displacement of fore part

Objective

Reducing thermal deformation of flange

↓

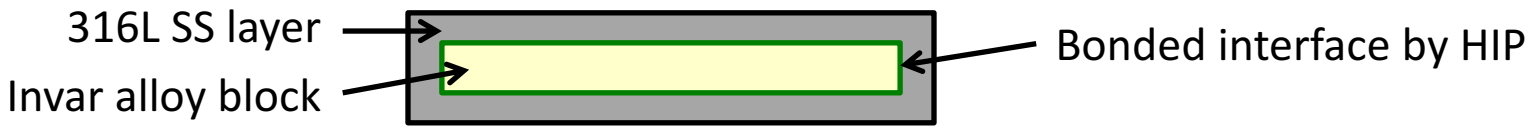
Applying invar alloy with low thermal expansion

Demerit ; Deformation of flange in invar alloy due to fastening by bolts is large
Low elastic modulus 140 GPa (316L SS : 200GPa)

↓

Combined material with low thermal expansion and high stiffness

Covering Invar alloy block with 316L SS layer and
bonding all interfaces by Hot Isostatic Pressing (**HIP**)



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Finding out suitable bonding conditions (Bonding temperature)

Requirements of diffusion bonding

- There is diffusion layer at interface.
- Bonding strength is larger than strength of bulk material.
- There is no degradation of mechanical properties of bulk material.
- Residual stress near interface is low to decrease mean stress relating with fatigue strength.

Specimens bonded with invar and 316L SS by HIP

- Structure observations
- Tensile tests
- Numerical analyses

Material and bonding condition

➢Materials

Chemical components

	C	Si	Mn	P	S	Ni	Cr	Mo	Fe
316L SS	0.018	0.58	0.83	0.026	0.001	12.11	17.62	2.08	Bal.
Invar alloy	0.005	0.25	0.23	0.003	0.002	36.11	-	-	Bal.

Important points in heat treatment

316L SS : Sensitization (600 - 800 ºC)

Invar alloy : No change of phase (500 - 1400 ºC)

➢Hot Isostatic Pressing

Bonding temperature: 700, 900, 1100, 1200 ºC

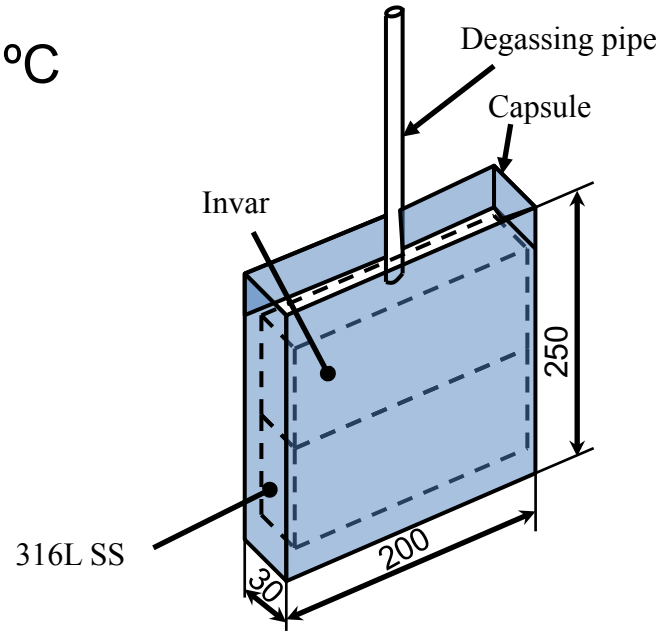
Heating rate: 573 ºC/h

Holding time:2h

Holding pressure:100MPa

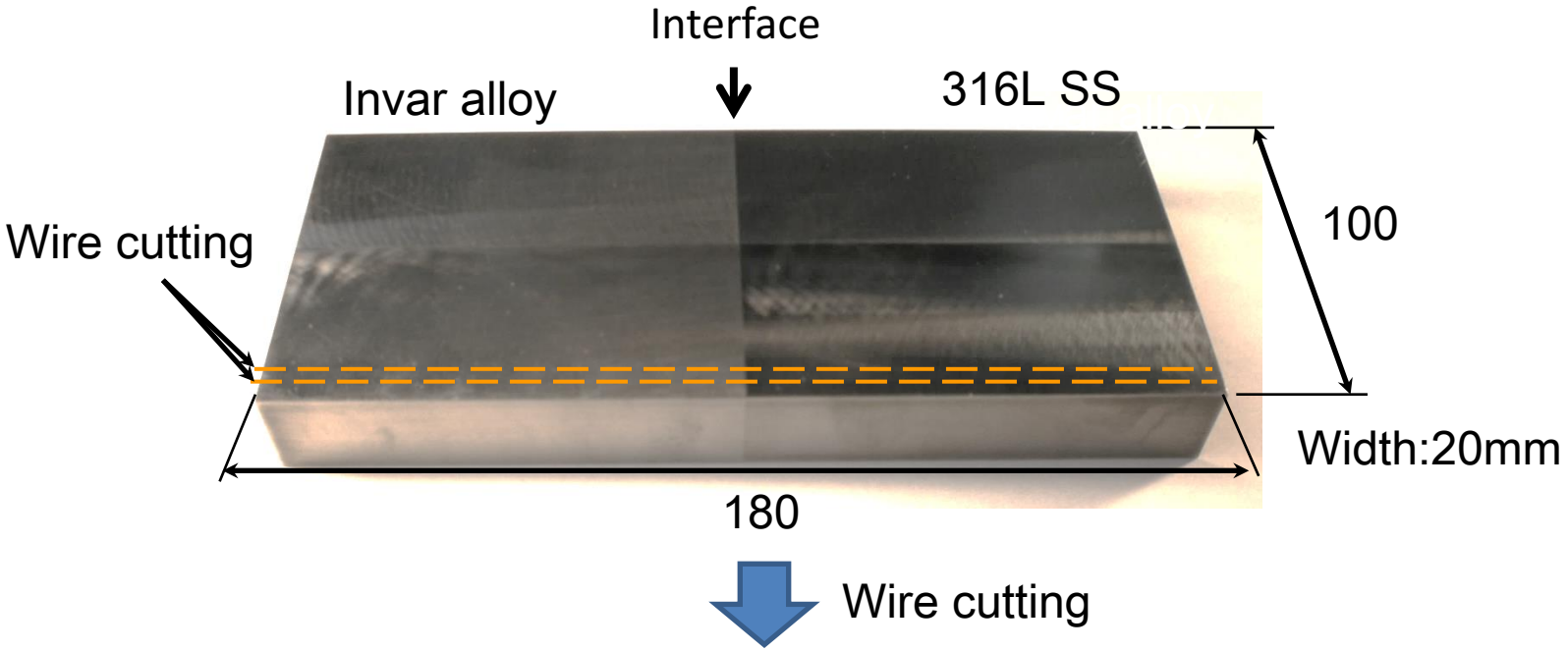
} were fixed

Materials were covered with capsule

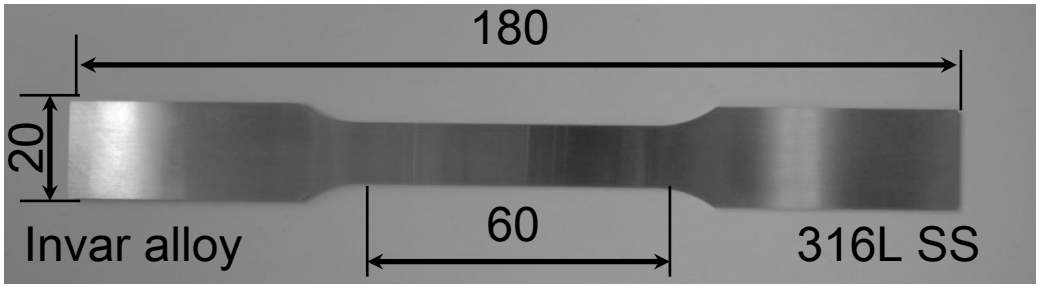


Specimen

Bonding material



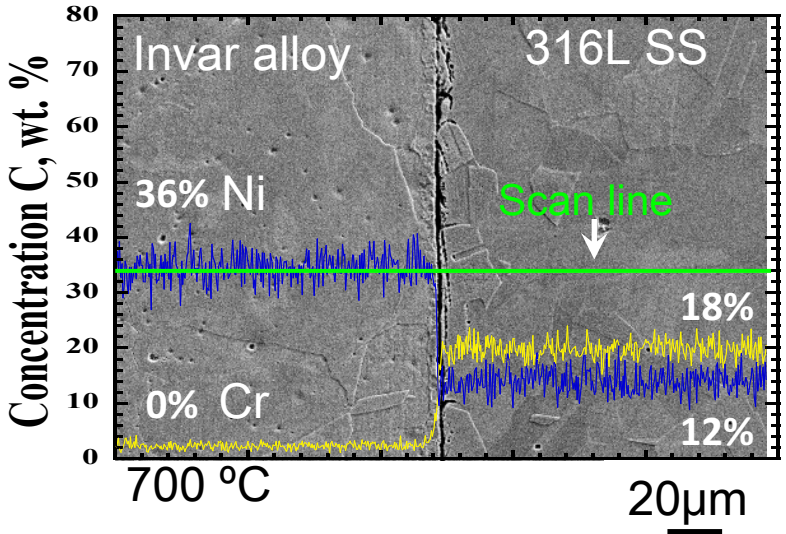
Tensile specimen (JIS 13 B plate type)

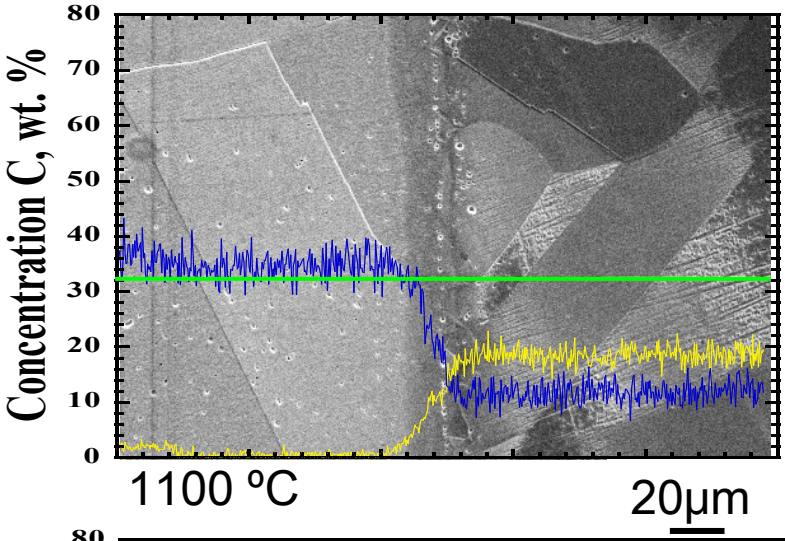


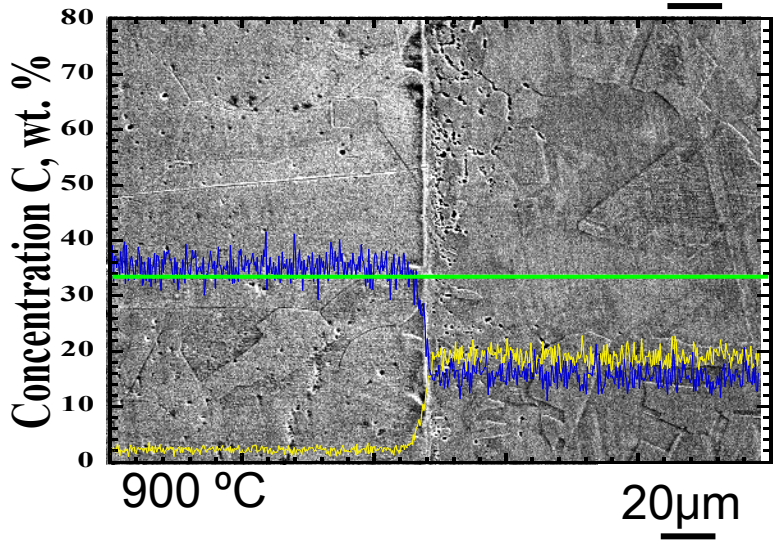
Thickness:2.5mm
Gauge part width:
12.5mm

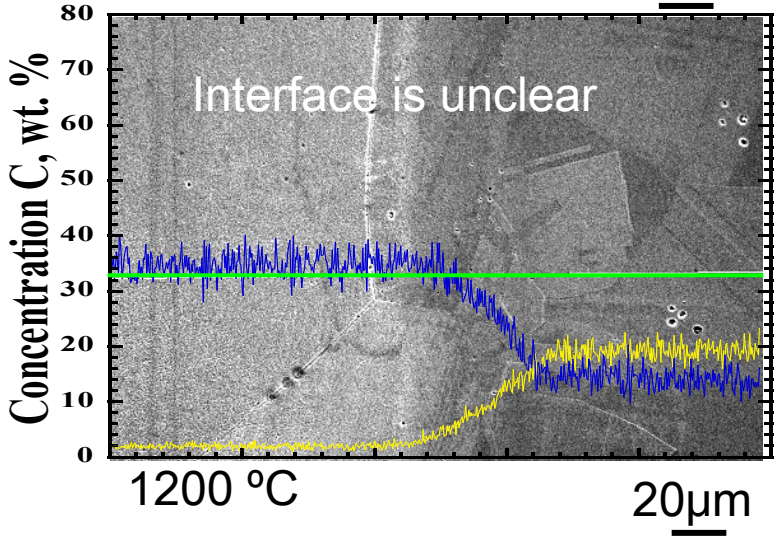
※JIS : Japan Industry standard

Concentration distribution





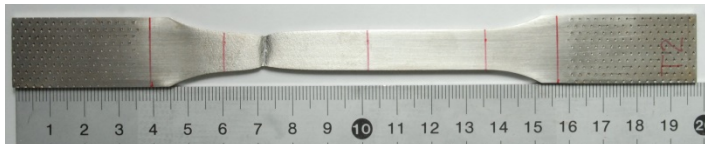




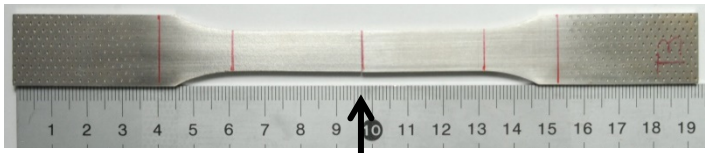
- **Concentrations of Ni and Cr change at diffusion layer.**
- **Specimen bonded at 700 °C has little width of diffusion layer.**

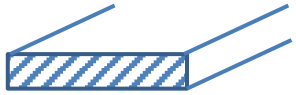
Result of tensile test (700 ºC)

Fracture position: IA side (4/6)

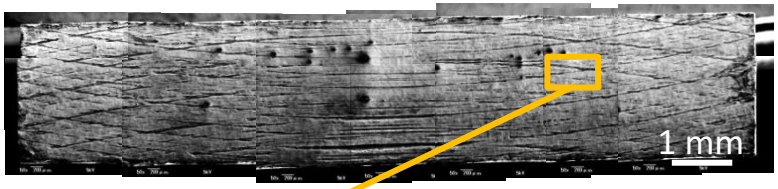


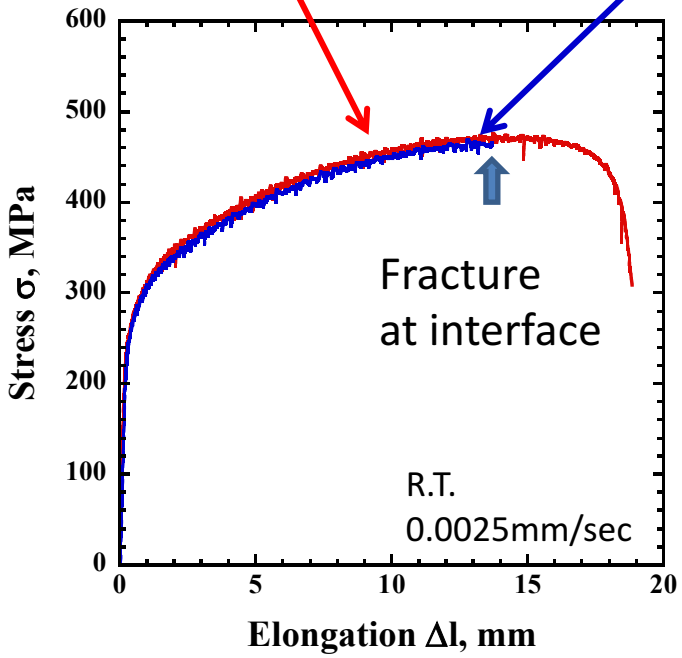
Fracture position: Interface (2/6)

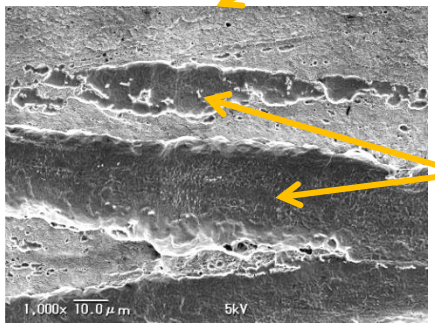




Fracture surface (Interface)



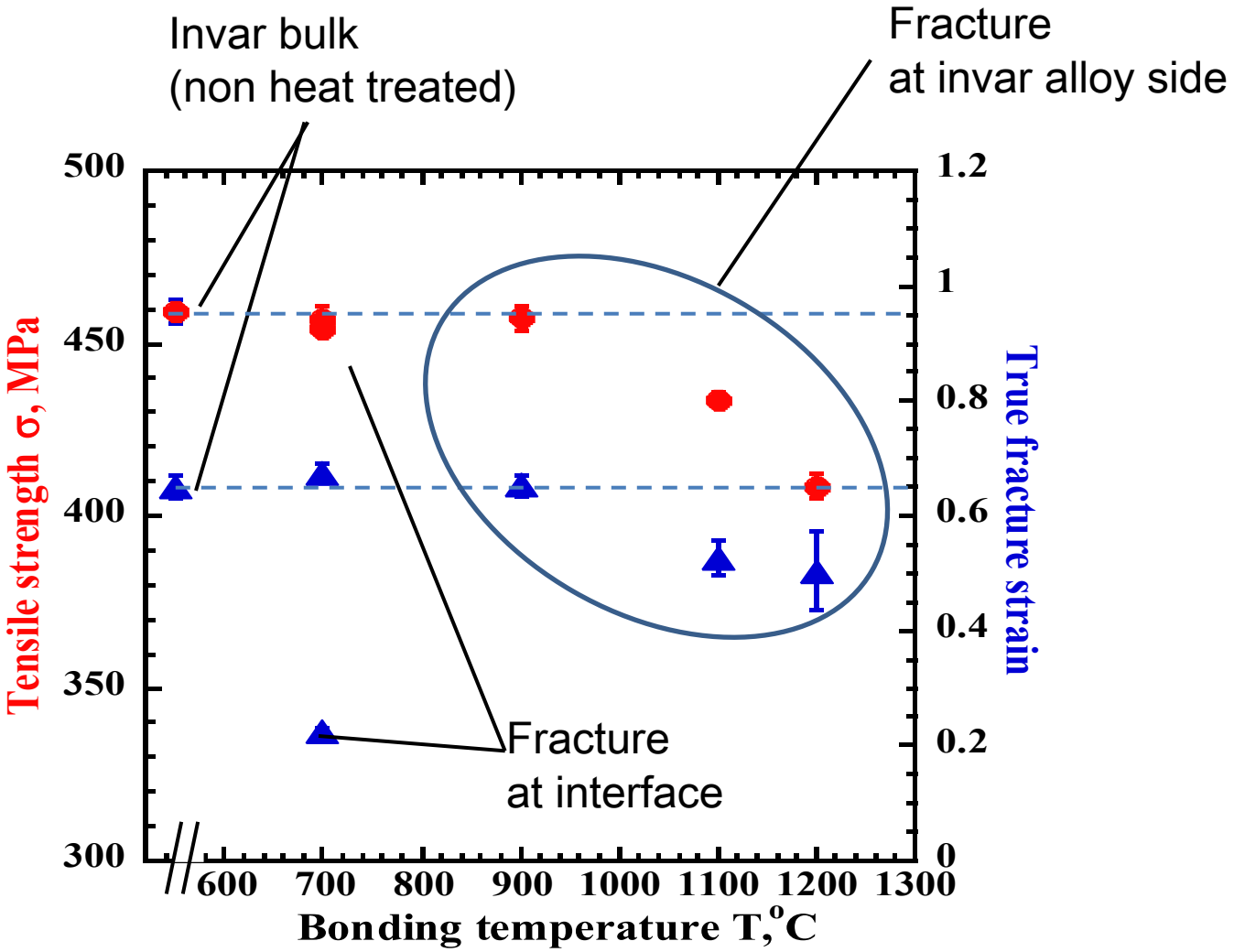




No bonding
(Scratch due to machining))

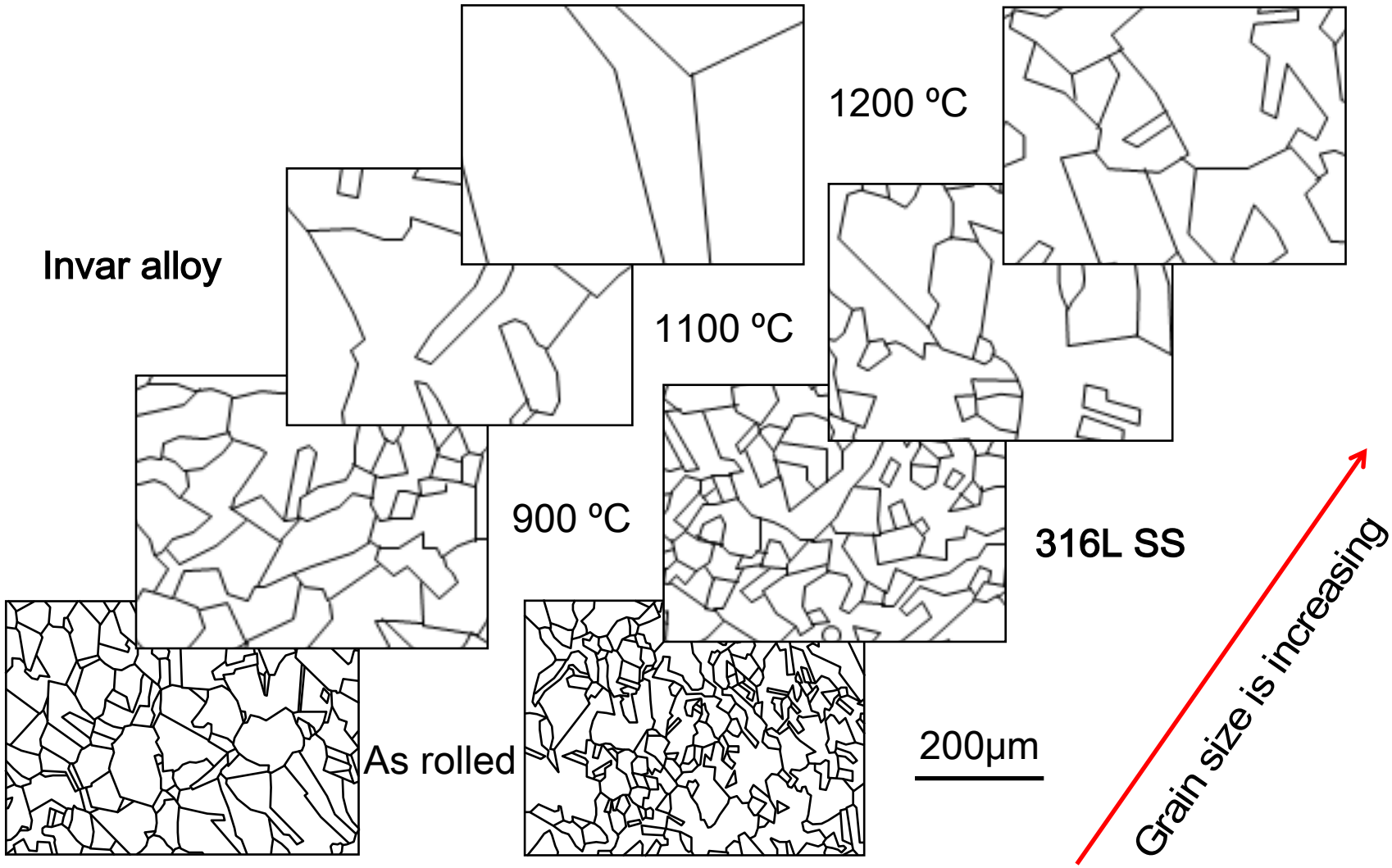
- **Some specimens fractured at interface.**
- **Non-bonding parts were observed on fracture surface of specimen which fractured at interface.**

Result of tensile tests on all specimens



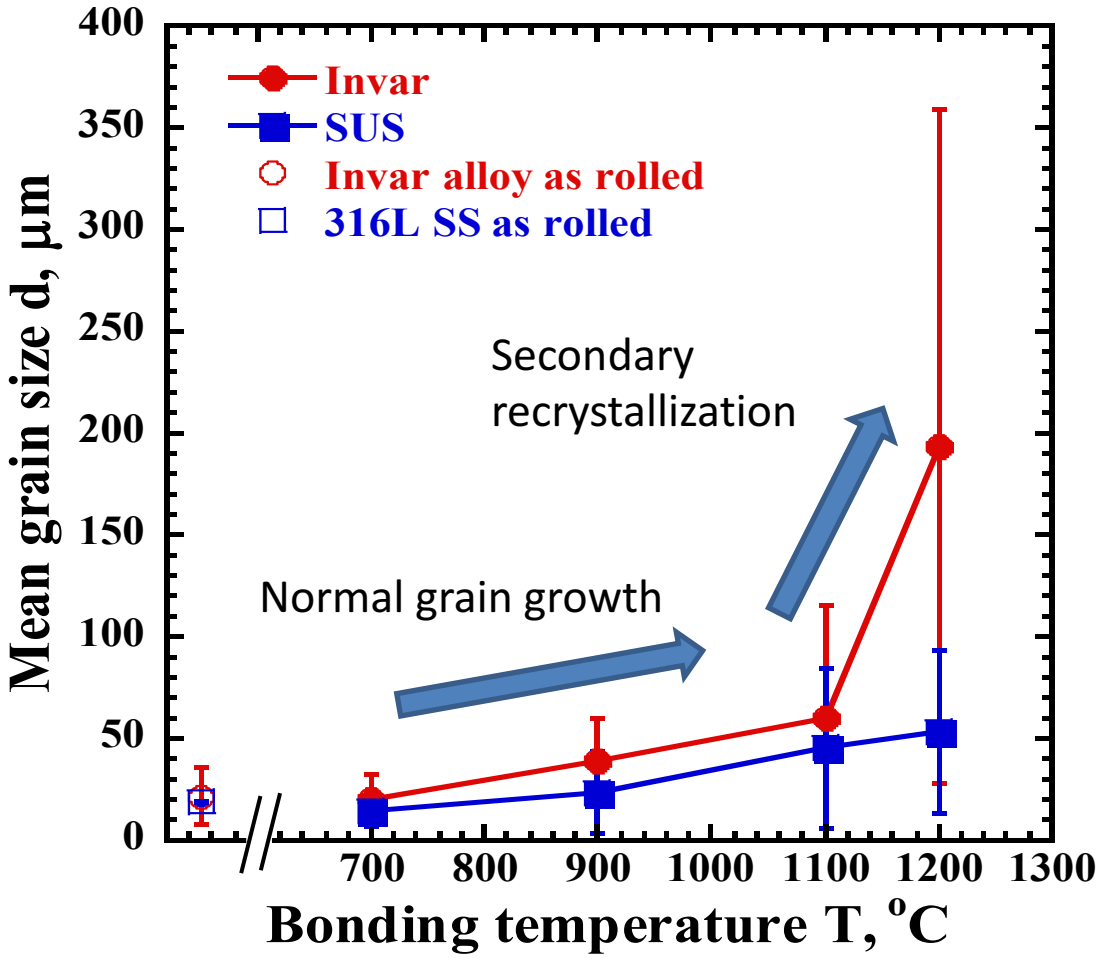
- Tensile property of specimen bonded at 900 ºC was same as result Invar bulk.
- Tensile property degraded in temperature condition over 900 ºC .

Metallographic structure of each bulk



- Grain size of Invar alloy was larger than that of 316L SS.
- Grain size of each material became larger with increasing boning temperature.

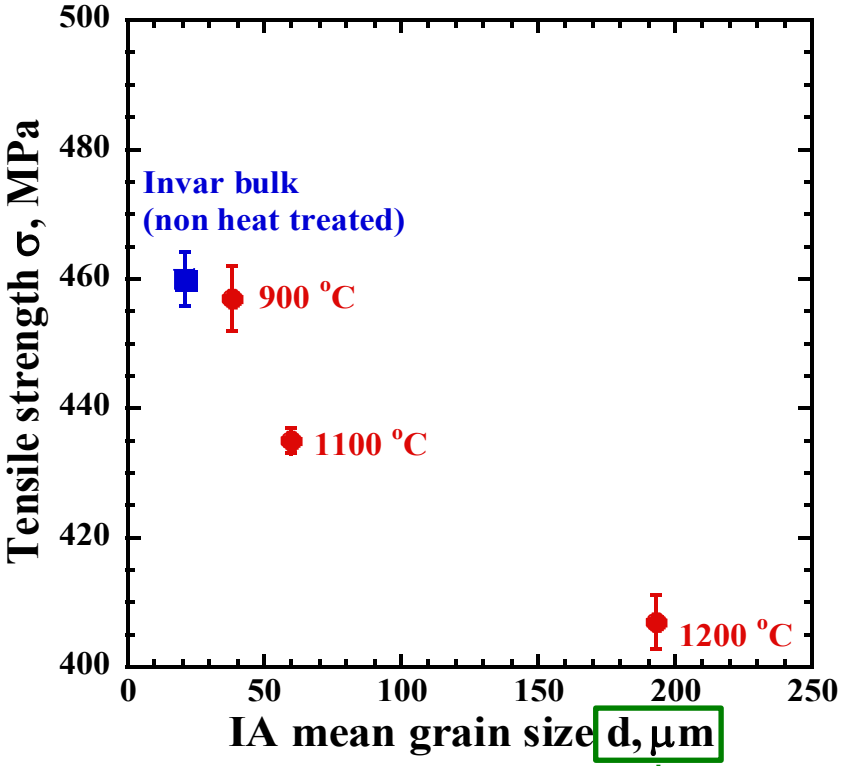
Effect of bonding temperature on grain size

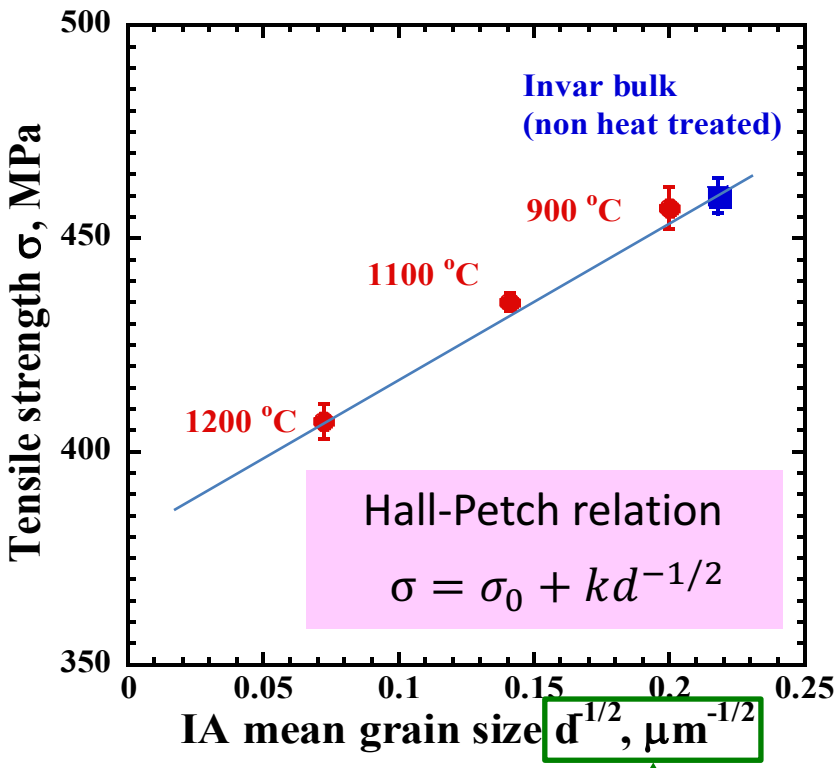


Grain size :
Equivalent diameter with same area

- Grain size of specimen bonded at 700 ºC was same as non heat treated material.
- Grain size increased with increasing bonding temperature.
- Secondary recrystallization in invar alloy bonded at 1200 ºC occurred.

Relationship between tensile strength and grain size



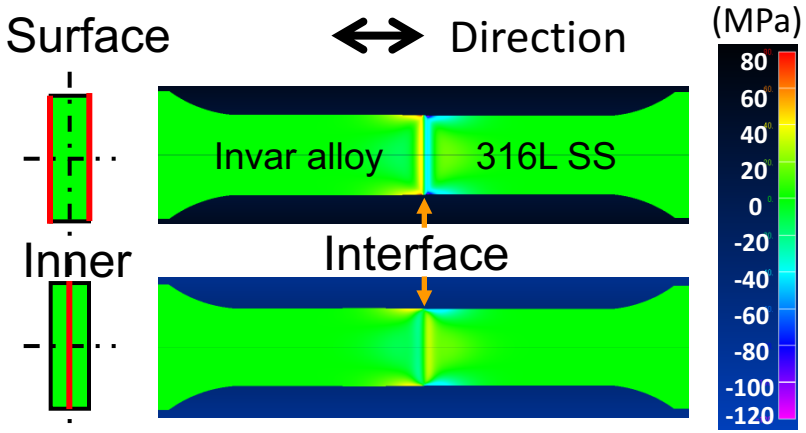


- Tensile strength decreased with increasing mean grain size of invar alloy.
- linearity in relationship corresponded to Hall-Petch relation.
- Tensile strength of bonded specimen was equal to that of invar alloy.

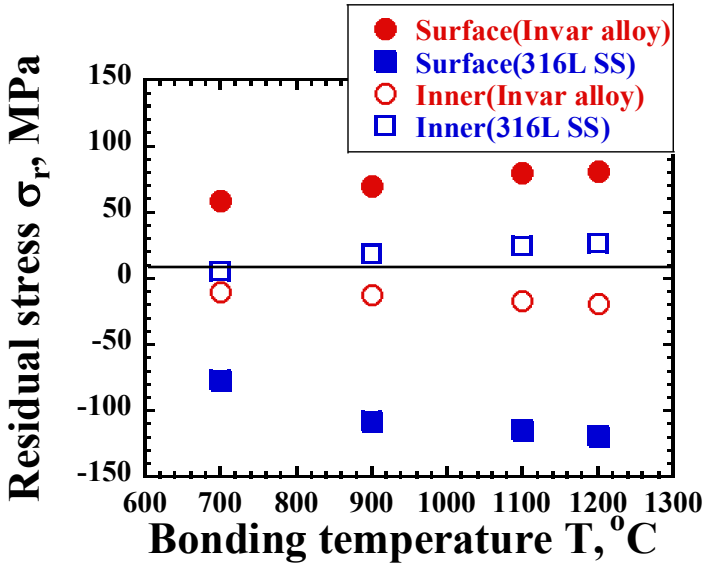
Residual stress estimated by FEM

FEM (Finite element method)

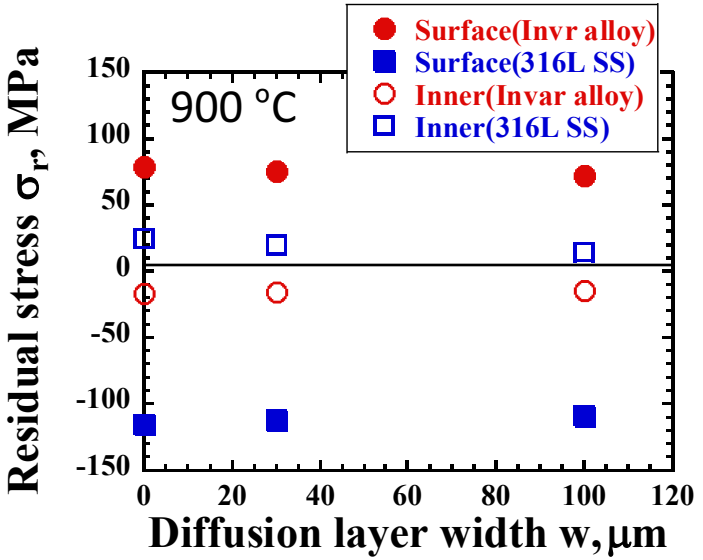
Code: Abaqus
Model : 1/4 model
Node : 78104
Element : 61400
Material : Thermal-Elastic-Plastic
Temperature : Bonding temperature
→Room temperature (20 °C)



Effect of Bonding temperature



Effect of thickness of diffusion layer



- **Residual stress increased with increasing bonding temperature.**
- **There is little effect of diffusion layer width on residual stress.**

Summary

	700 °C	900 °C	1100 °C	1200 °C
Diffusion layer (Thickness)	4	3	2	1
Bonding strength	4	1	?	?
Tensile strength of bulk	?	1	2	3
Corrosion resistance of bulk	4	1	1	1
Residual stress	1	2	3	4

1 : Best – 4 : Worst
? : Undeterminable

Best bonding temperature is 700 °C in above test conditions.

In the future,

Best thickness ratio of 316L SS and invar alloy will be found out taking into account of thermal deformation and stiffness of flange.

Residual stress on surface