13th International Workshop on Spallation Materials Technology
30 October - 4 November 2016

# Failure analysis on the welded part with steep change of thickness employed in JSNS mercury target vessel

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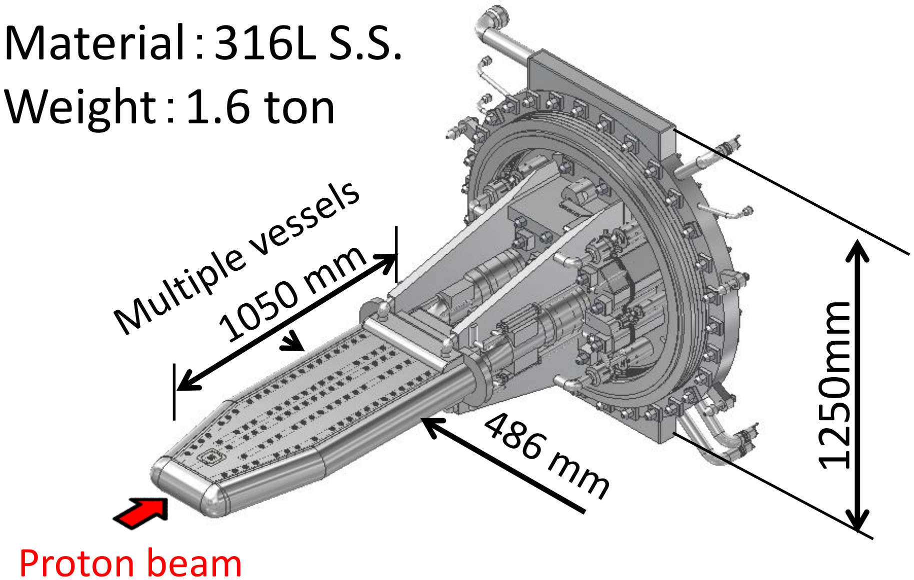
# Outlines

- Water leakage from mercury target in JSNS
  - Structure of mercury target
  - Occurrence of water leakage
- Cause analysis on leakage
  - Stress and crack propagation analyses to estimate water leak position
  - Welding test with partial mockup model
  - Numerical analysis simulating welding process
- Summary

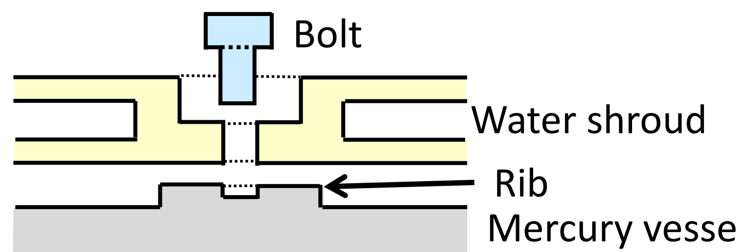
# Structure of JSNS mercury target vessel

JSNS: Japan Spallation Neutron Source

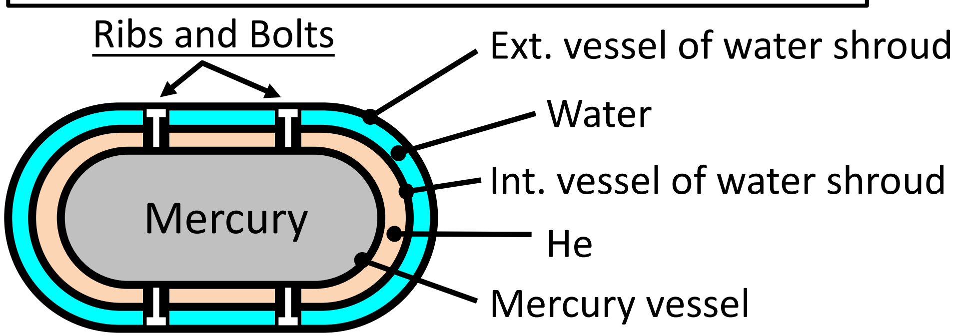
Material：316L S.S.
Weight：1.6 ton




- Mercury target vessel consists of mercury vessel and double walled water shroud (internal and external vessel) which prevents spreading of mercury in case of mercury vessel failure.
- Most of water shroud is put on ribs outside of mercury vessel and fixed by bolts. And , seal welding around bot was carried out.




Vertical cross section of target vessel viewed from target front



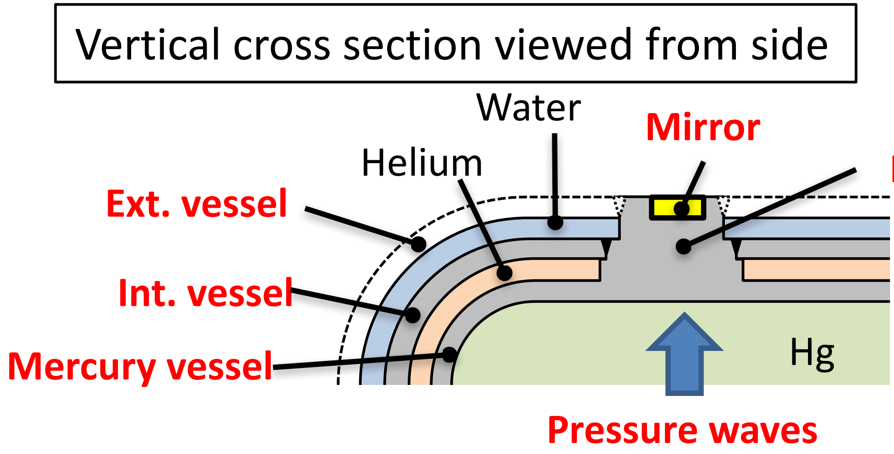

Applied loads

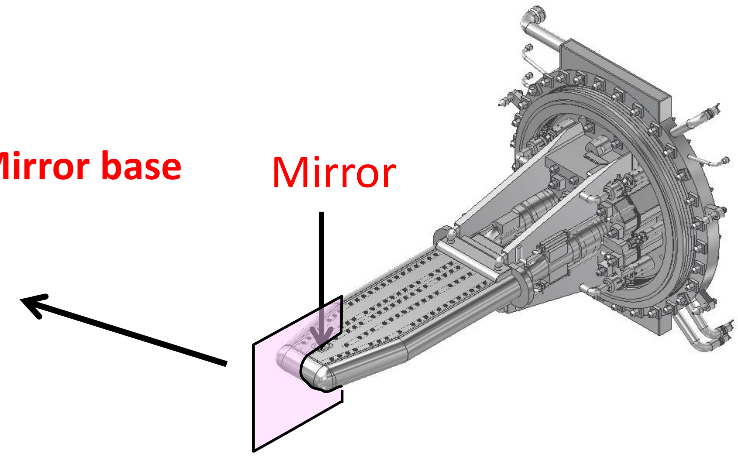
Static pressure

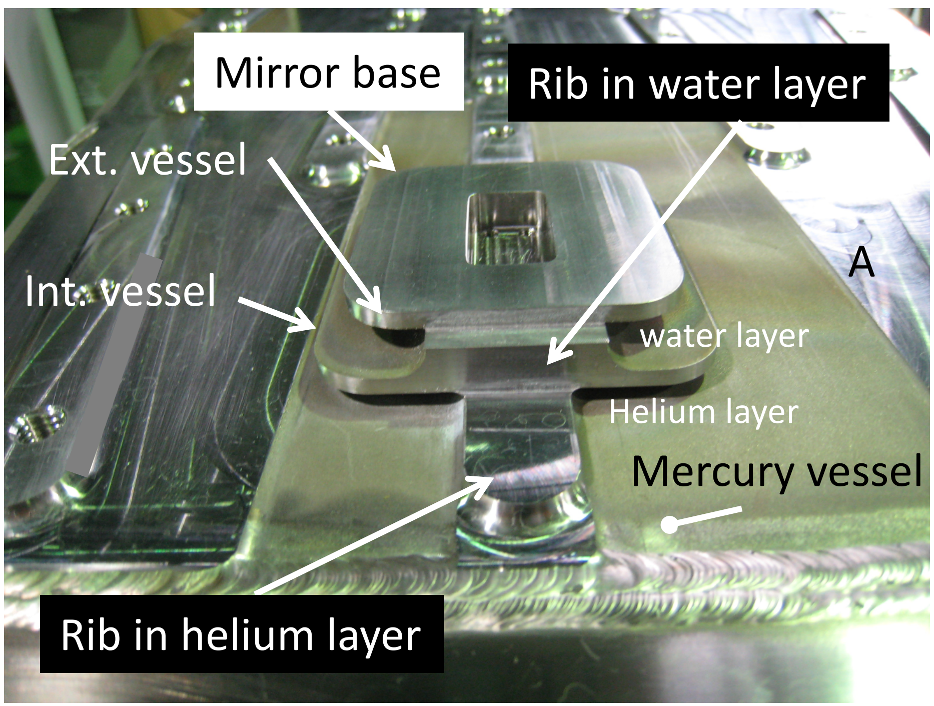
Thermal stress: repeated by beam trip

Pressure waves: applied in 25 Hz

# Unique structure in JSNS mercury target



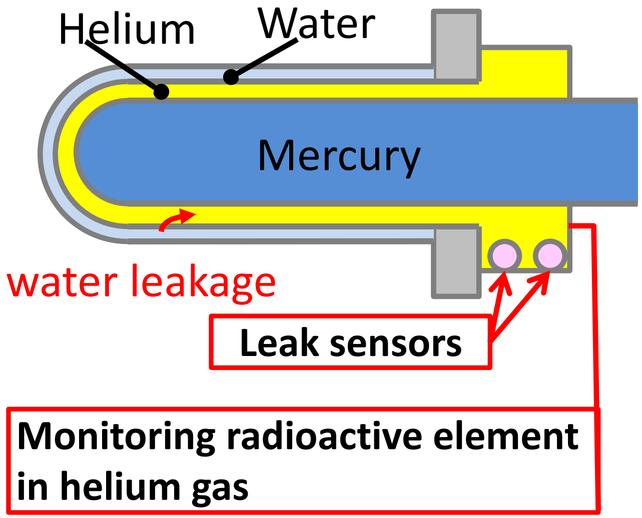

Upper surface of mercury target

- In order to measure vibration of mercury vessel due to pressure waves, mirror is set on mirror base which has monolithic structure with mercury vessel.
- Parts around mirror base were welded with water shroud.

# Occurrence of water leakage

When total time of beam operation with beam power of 500 kW was about 300 hours (2.8 x $10^7$ beam pulses),

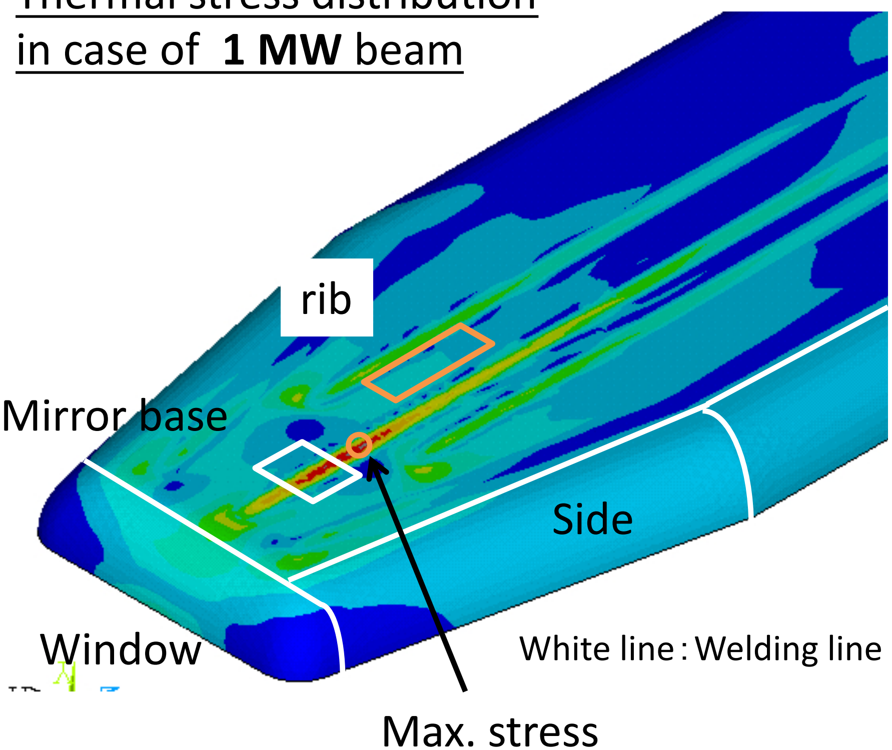
- warning from leak sensor set in space between mercury vessel and water shroud was issued,
- but any radioactive elements indicating mercury leak was not monitored by radioactive monitor.

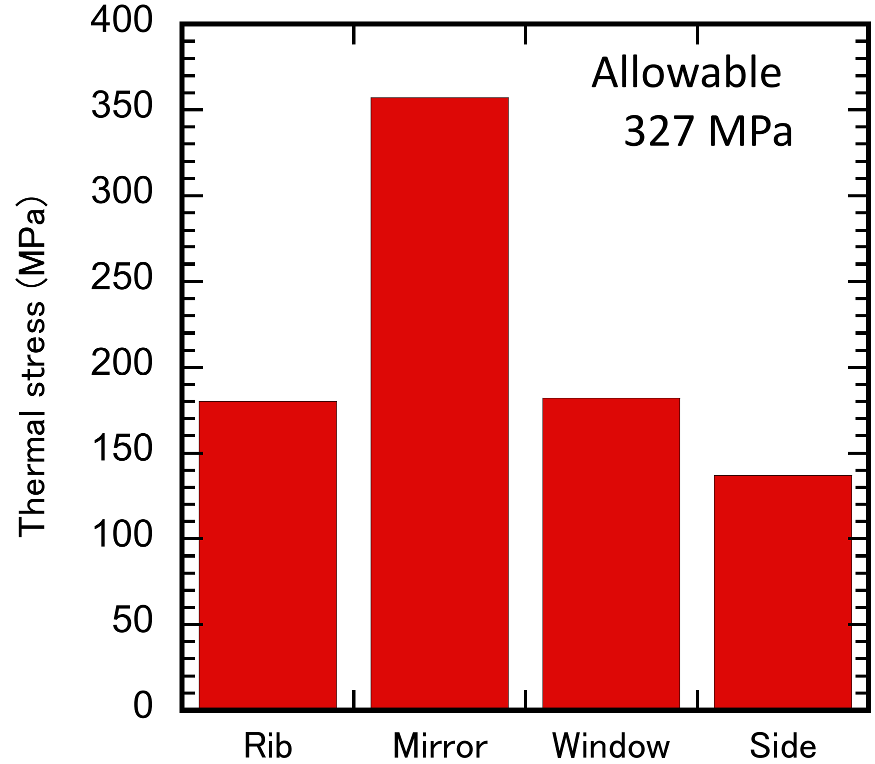



**Leakage of water from water layer to he layer occurred.**

# Estimation of thermal stress due to temperature rise in beam operation

Thermal stress distribution in case of **1 MW** beam



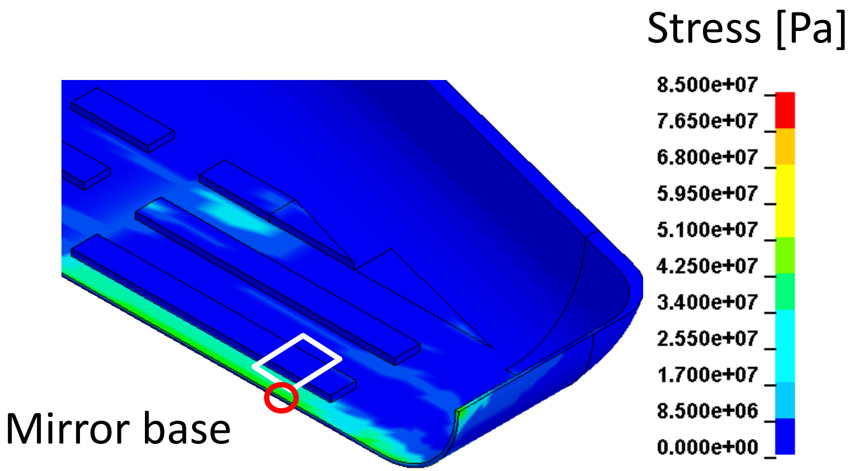



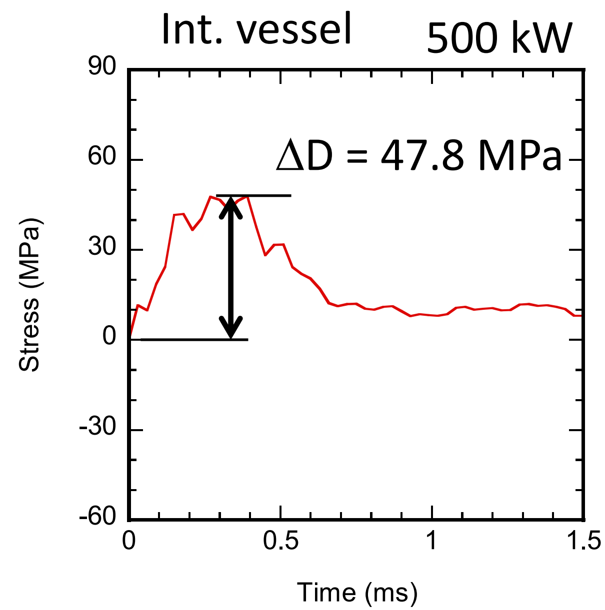

- Max. stress of 350 MPa was generated around mirror base at 1 MW.
- **In 500 kW operation**, it was **175 MPa** which was **lower than allowable stress**.
- **Stress range due to beam trip was also lower than allowable stress range** for 760 cycles-fatigue**.**

*760 cycles; Number of beam trip in 500 kW operation with this target

# Estimation of dynamic stress due to pressure wave

Dynamic stress distribution on inner surface of Int. vessel in beam power of 500 kW at 0.39 ms after beam shot.



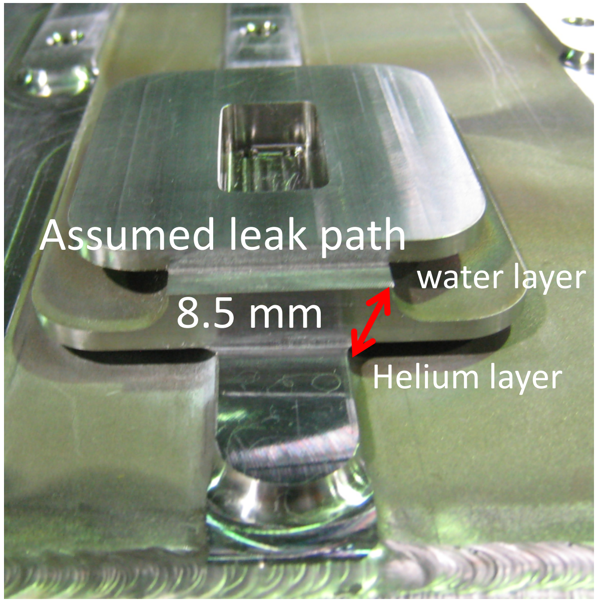




Allowable level:
$\Delta D$ < 160 MPa (for 5 x $10^8$ pulses)

Stress range, **$\Delta D$, on mirror base** was about **48 MPa** which was **lower than allowable level** for fatigue.

**Internal vessel was hardly failed by stress in case of no initial defects.**
**Conversely, it was predicted that there was initial defect.**

# Estimation of initial crack length inversely assuming that crack propagates from helium layer to water layer

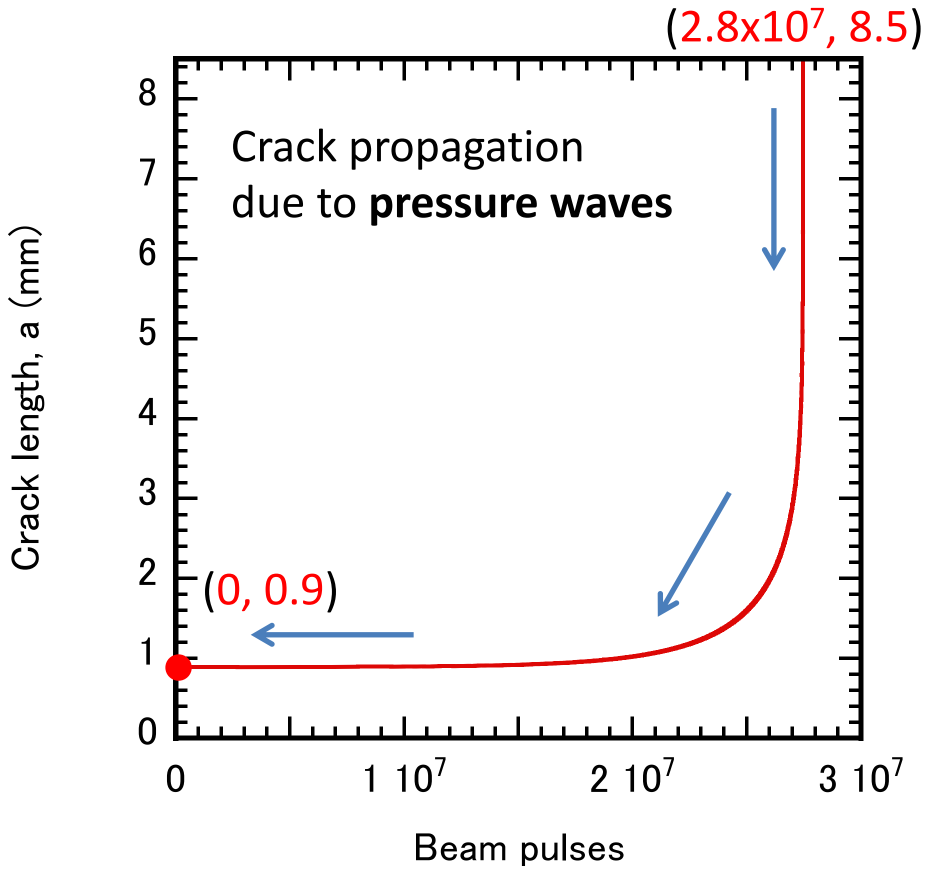



$$da/dN = C\Delta K^m \qquad \Delta K = F\Delta\sigma\sqrt{\pi a}$$

$a$ : Crack length
$\sigma$ : Stress calculated in num. simulation

C=1.4142x$10^{-11}$
m=2.8725

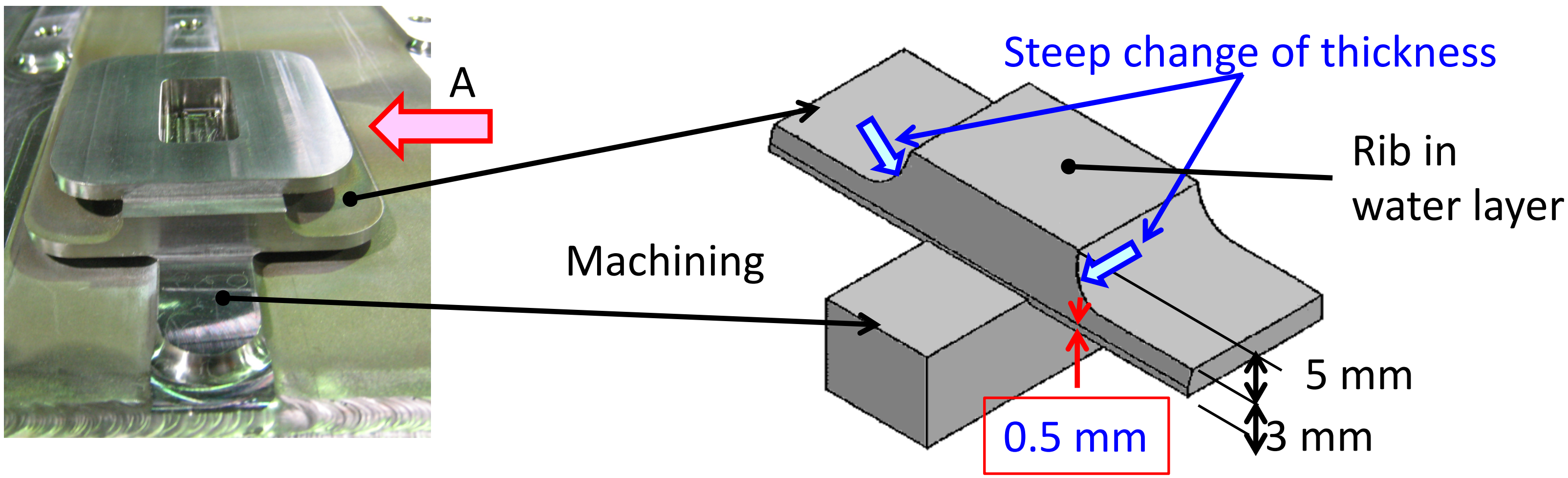
Welded austenite stainless steel
(Fatigue data sheet made by National Research Institute for Metals)

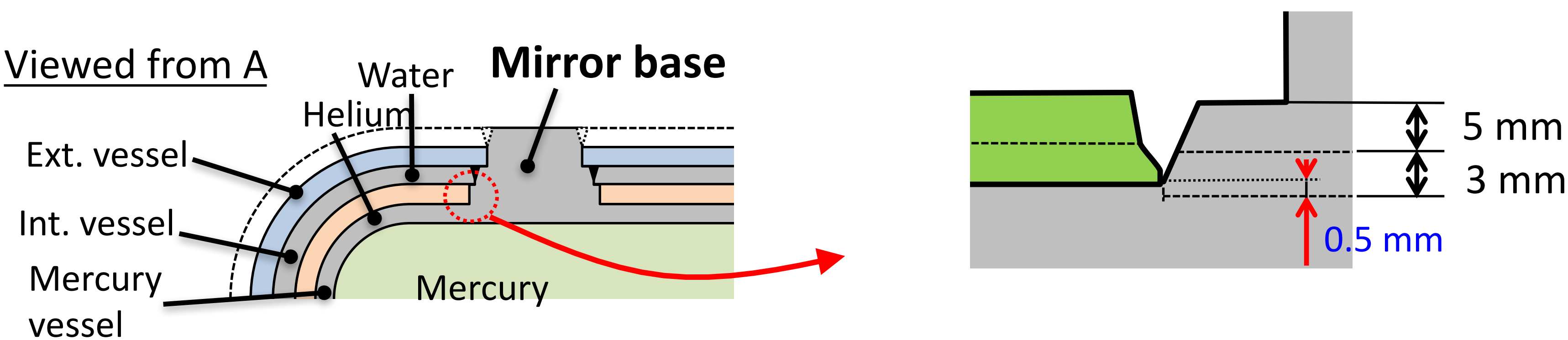



Initial crack of more than 0.9mm at mirror base has possibility to penetrate between water layer and helium layer.

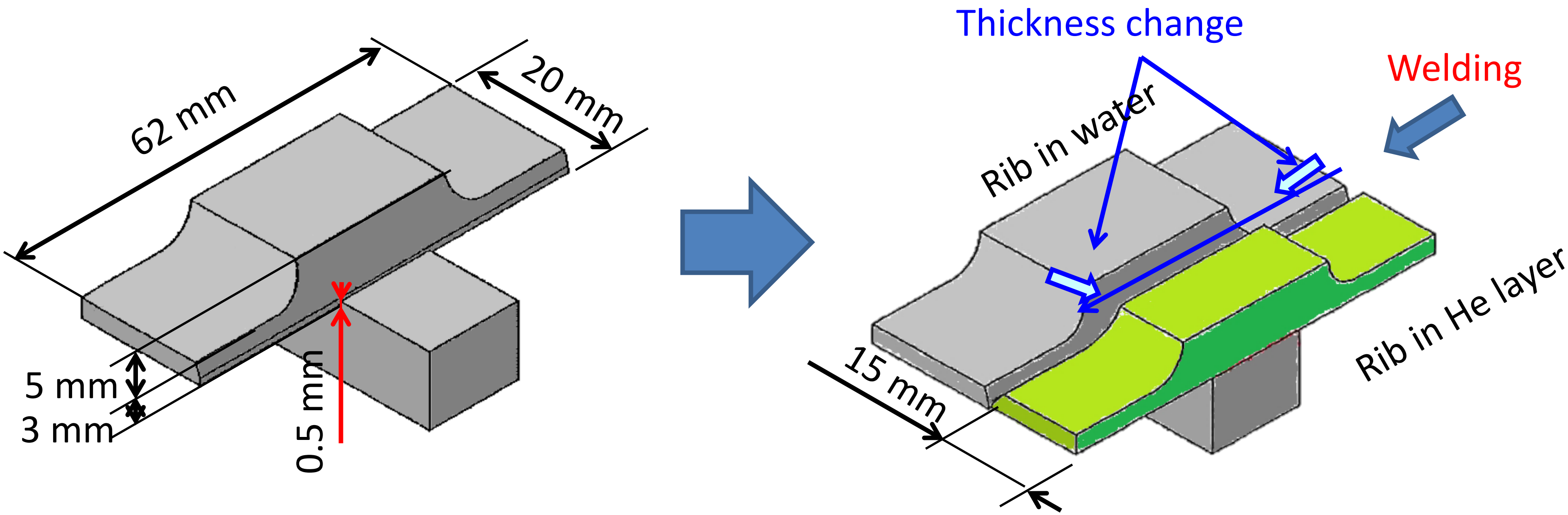
# Investigation on fabrication process around mirror base

1. Welding assembly of mercury vessel
2. Machining top surface of ribs in helium layer to put water shroud
   Step of about 0.5 mm caused.
3. Welding assembly of int. and mercury vessels
   Welding mirror base and int. vessel with steep change of thickness was carried out.



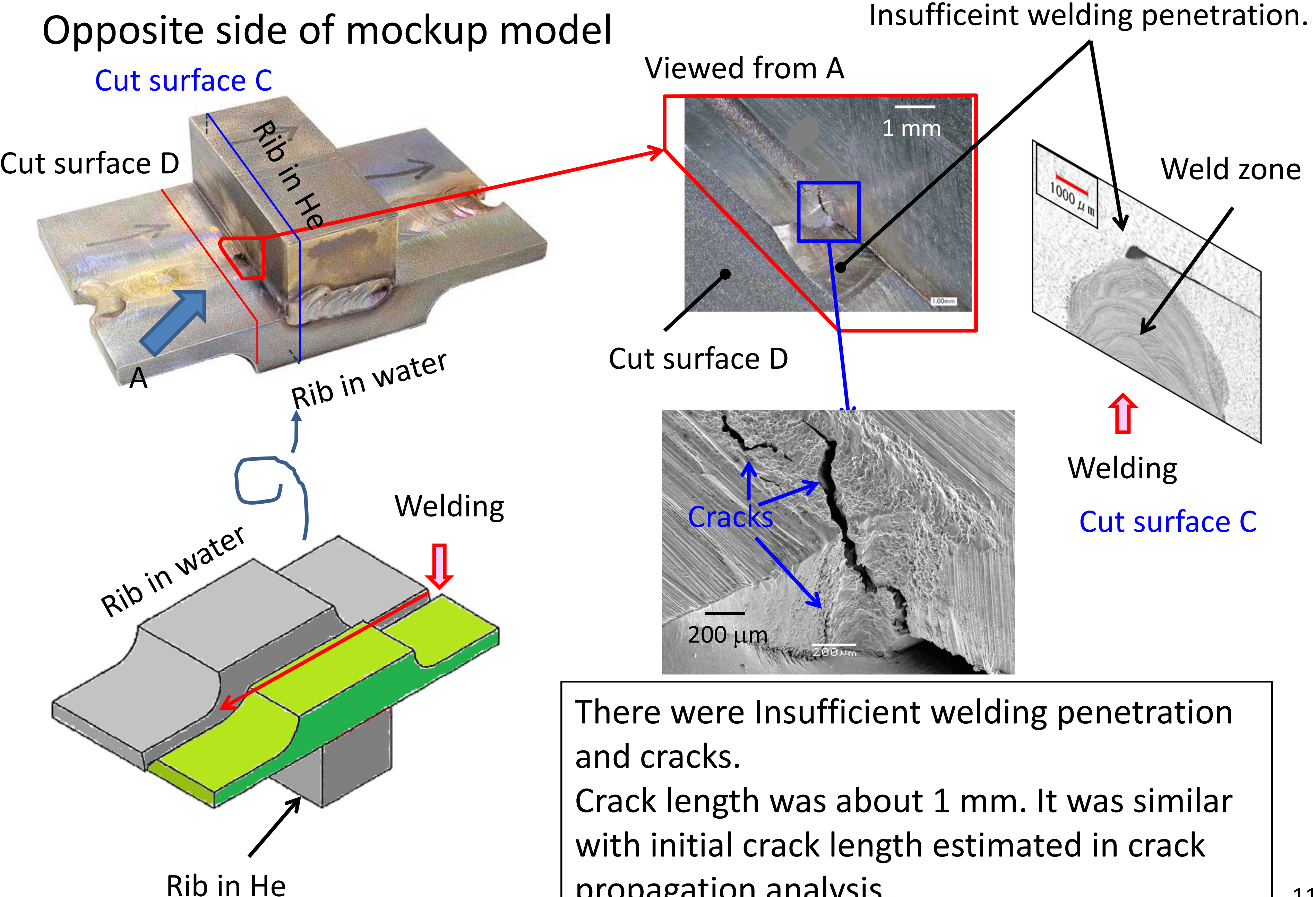



# Welding test using partial mockup model to confirm that there were initial defects on welding around mirror base



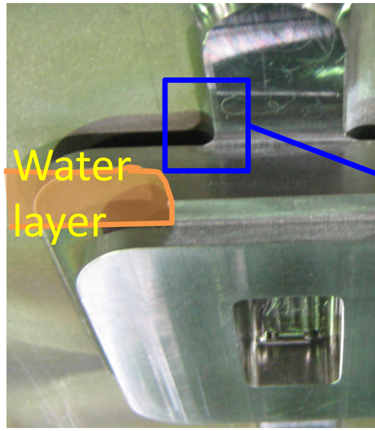

Welding condition was same with that in fabrication process of real target.

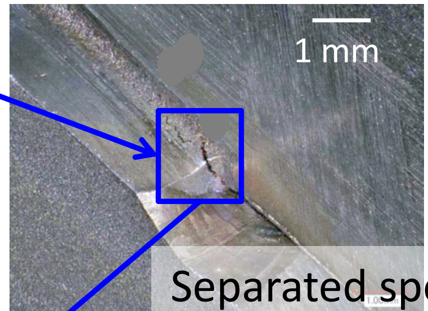
# Result of welding test using mockup model



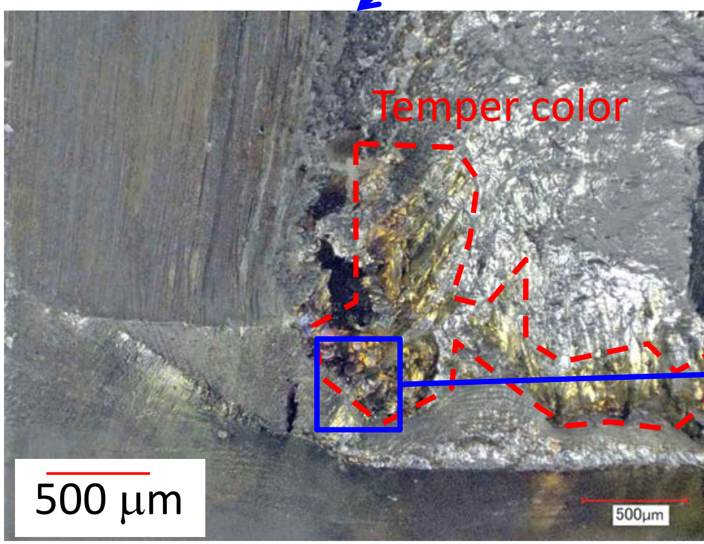

There were Insufficient welding penetration and cracks.
Crack length was about 1 mm. It was similar with initial crack length estimated in crack propagation analysis.

# Observation of fracture surface to investigate crack in detail

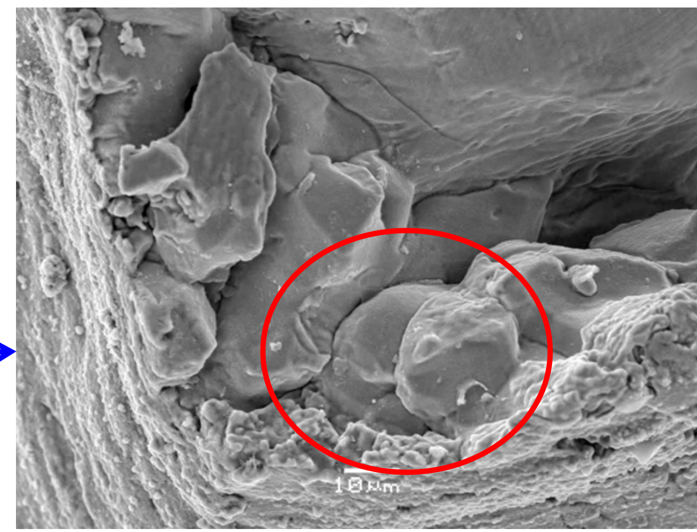



Separated specimen for observation of fracture surface



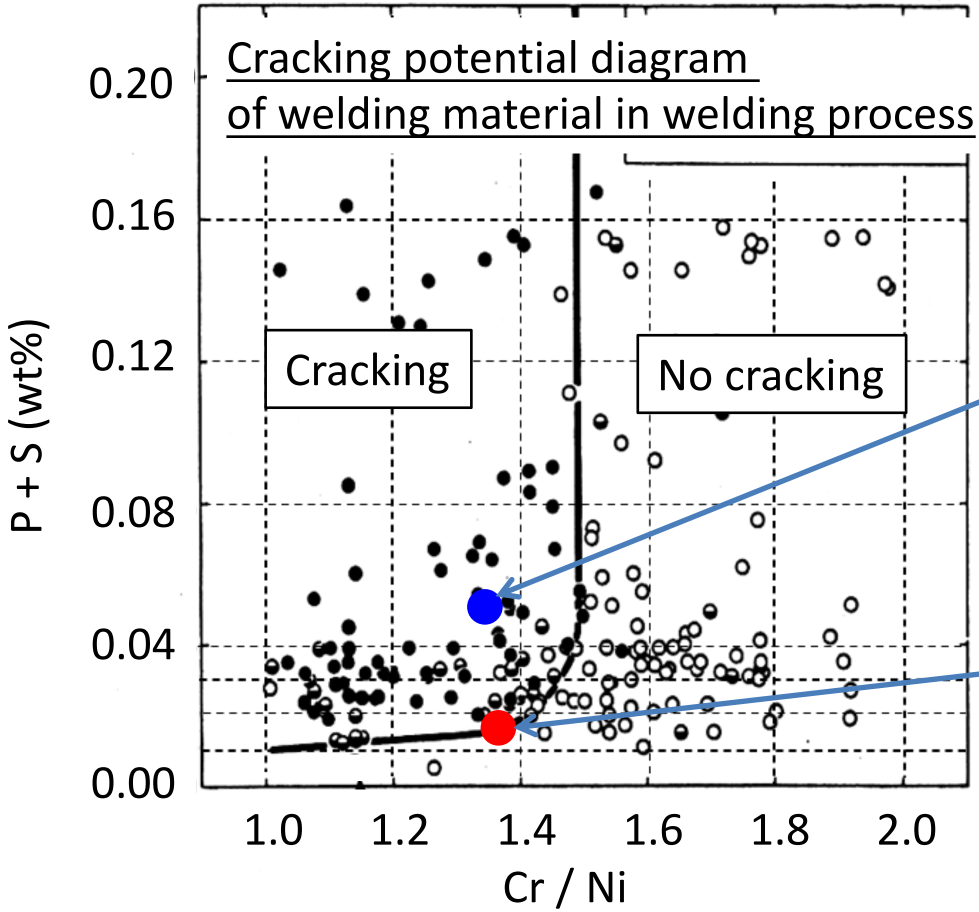

Temper color was marked by exposure at high temperature.
It indicated that crack was opened during welding process.



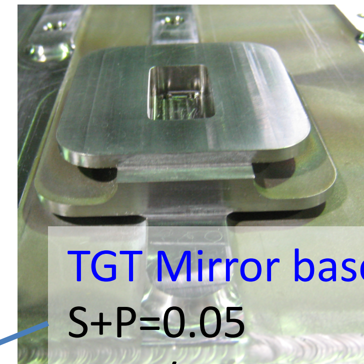
Intergranular crack surface was observed partially.

# Effect of chemical composition on cracking in welding process

It is known that welding material is cracked with Intergranular when P and S are rich.




V.P.Kujanpaa et.al, Weld. Res. Int. 9-2(1979)



TGT Mirror base*
S+P=0.05
Creq/Nieq=1.38

Mockup*
S+P=0.026
Creq/Nieq=1.39

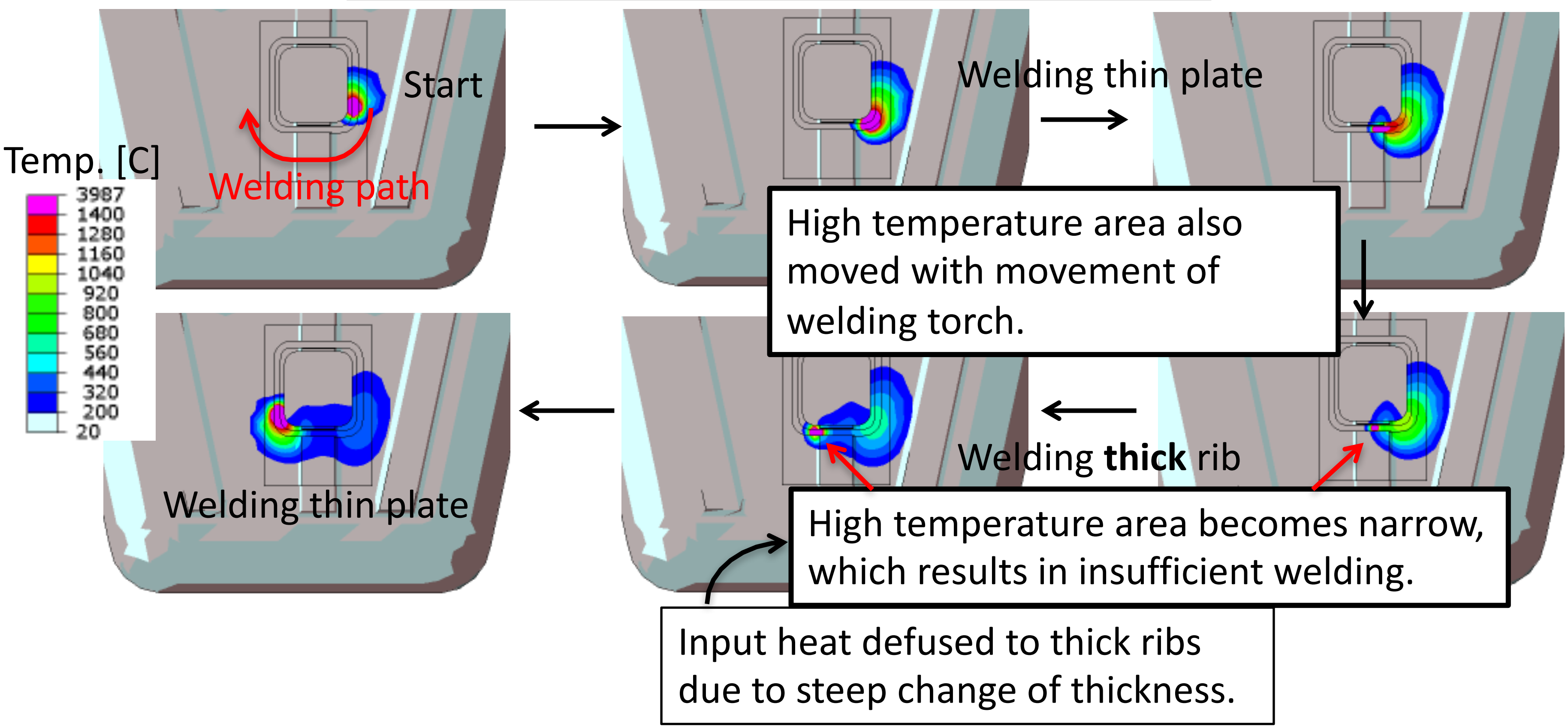
*Chemical compositions of materials were inside range of regulation for 316L SS

Mockup was cracked although composition data was on border of diagram.
There is large possibility that crack occurs in mercury target.

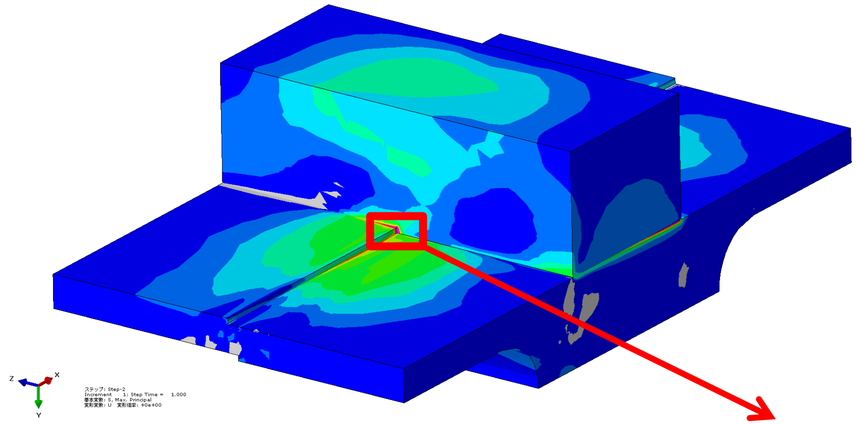
# Numerical analysis simulating welding process to investigate why insufficient welding occurred

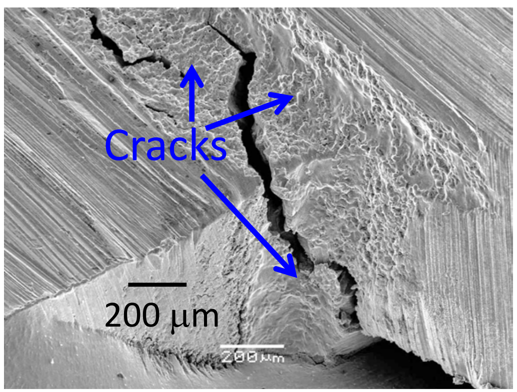
Numerical analysis
1. Setting meshes of 1st layer of welded metal
2. Inputting constant heat while moving it with constant speed as moving welding torch
3. Repeating 1 and 2

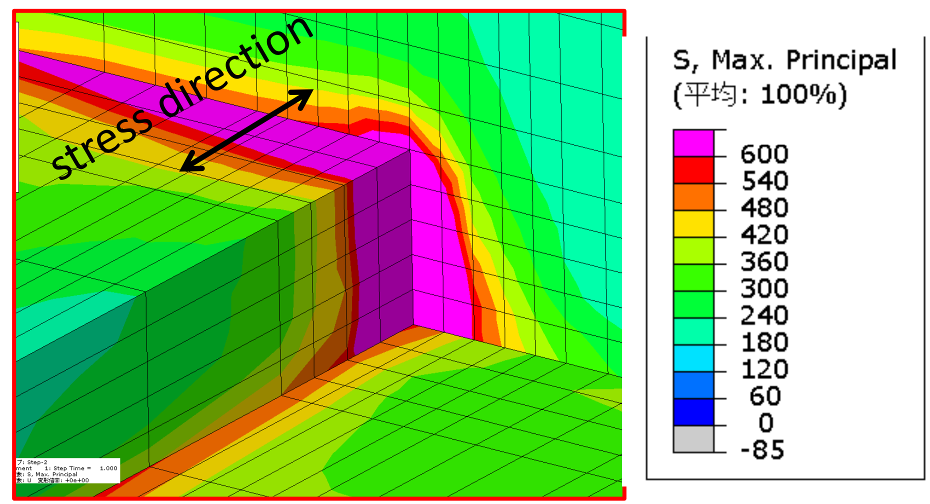
Result: Temperature distribution in 1st layer welding



# Stress distribution on part which cracks occurred






Tensile stress over tensile strength of 480MPa was generated
due to stress concentration caused by insufficient welding and step.

This high tensile stress caused initial cracks

# Summary

Cause analyses on event that water leaked from water shroud to inside were carried out. Mirror base was focused because it had steep change of thickness on welding line.

- Generated stresses on structure without defects were less than allowable level in 500 kW operation.
- Welding test simulating welding process in real target showed insufficient welding and generation of crack.
- Crack length was about 1 mm which had potential to generate water leakage path around mirror base due to beam pulse of $2.7 \times 10^7$ pulses in 500 kW operation.
- In numerical simulation in welding process, high temperature region became narrow at position where thickness of welding line changed to thick. This would cause insufficient welding at thick welding position.
- Low compositions of P and S, and high composition ratio of Cr/Ni might be effective to suppress cracking in welding process.

# Future works

For robust welding in target, investigations of effects on cracking in welding process of

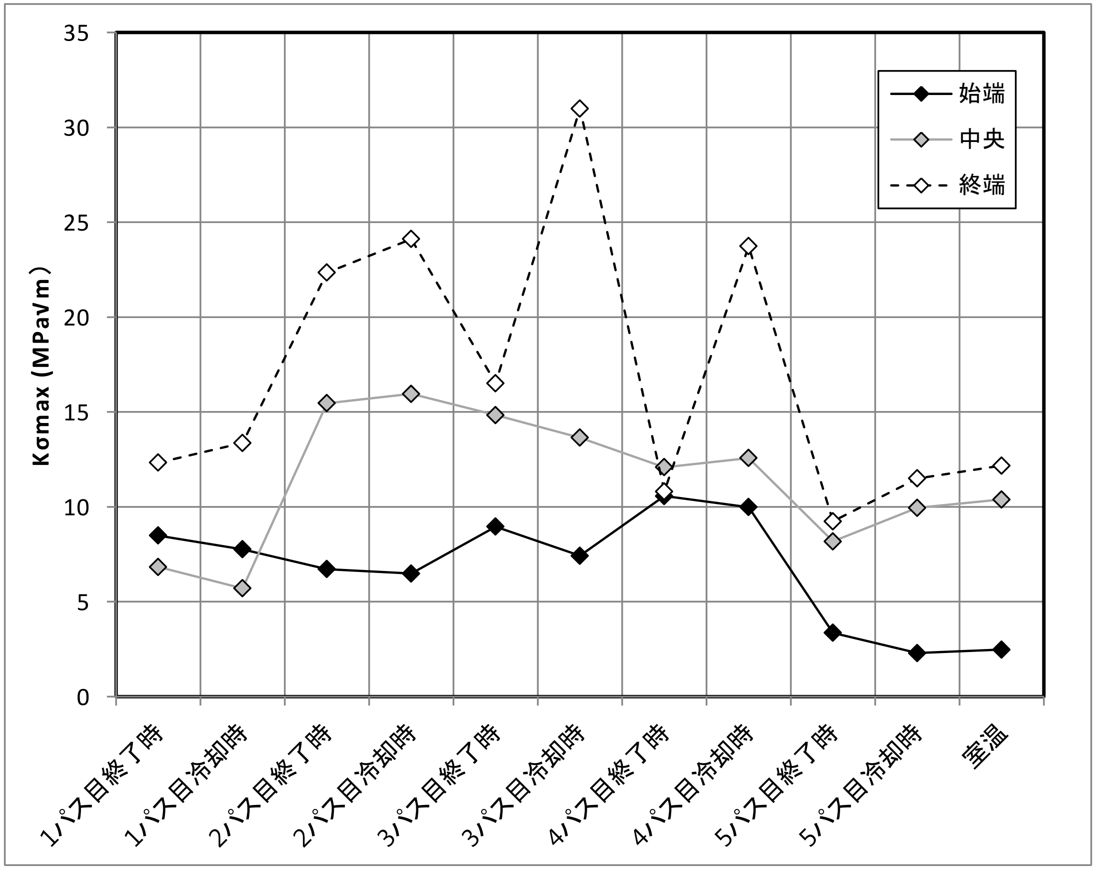
- Chemical composition in 316 L SS
- Surface roughness due to machining

will be carried out.

# Welding condition

a. Volts：11 V
b. Amps：80～120 A
c. Weld speed：6～8 cm/min (the 1st pass: 6 cm/min, 2nd pass: 7cm/min, 3rd: 8 cm/min）
d. Wire feed rates：ー
e. Tack weld location：Figure below
f. Filler material：NS-316LR
g. Pre-heat, interpass temperatures (and more info if additional PWHT was applied ): Pre-heat: None、Interpass temp.: room temp., PWHT: None
h. Start/stop location identification：Near tack weld location (No record)
i. Any history documents：-

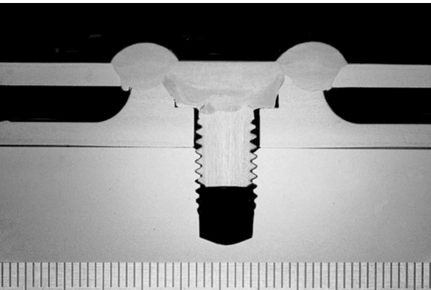
# 溶接過程における応力拡大係数




3パス終了後の冷却時に終端部で$K_{σmax}$=31 MPa√m生じるが、SUS316L材の破壊靭性※よりも低いレベルにあると思われる。

※電中研資料　キャニスタ材料の健全性（第5章）　図5-4-7より
316(LN)(HAZ) $J_i$ ≒100 kJ/$m^2$, K換算≒145 MPa√m

# 成分分析結果



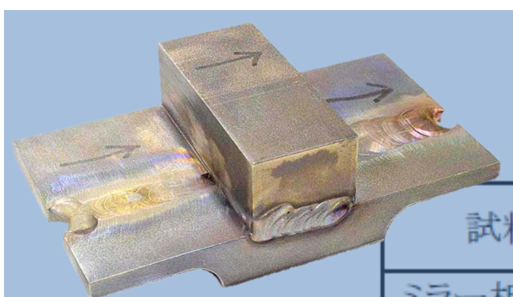
模擬試験体の一部を溶解して分析

成分分析結果（ボルト部母材）

単位wt%

| 試料 | C | Si | Mn | P | S | Ni | Cr | Mo | N |
|---|---|---|---|---|---|---|---|---|---|
| ボルト部板材 | 0.028 | 0.53 | 0.87 | 0.033 | 0.001 | 12.09 | 17.75 | 2.14 | 0.0370 |
| JIS SUS316L | ≦0.030 | ≦1.00 | ≦2.00 | ≦0.045 | ≦0.030 | 12.00～15.00 | 16.00～18.00 | 2.00～3.00 | — |

き裂発生部の溶接による応力は比較的低いが、
Pの量が多い



成分分析結果（ミラー部相当箇所材）

単位wt%

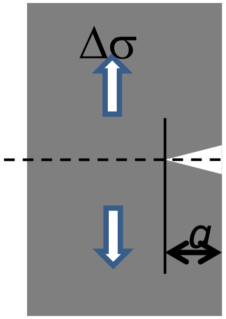
| 試料 | C | Si | Mn | P | S | Ni | Cr | Mo | N |
|---|---|---|---|---|---|---|---|---|---|
| ミラー相当箇所 | 0.017 | 0.42 | 0.84 | 0.025 | 0.001 | 12.06 | 17.21 | 2.05 | 0.0424 |
| JIS SUS316L | ≦0.030 | ≦1.00 | ≦2.00 | ≦0.045 | ≦0.030 | 12.00～15.00 | 16.00～18.00 | 2.00～3.00 | — |
| ミルシート | 0.012 | 0.42 | 0.85 | 0.023 | 0.000 | 12.09 | 17.40 | 2.09 | |

# Estimation of crack propagation due to repeated stress

Initial crack, such as insufficient welding, was assumed.
Crack propagation length, *a*, was calculated based on fracture mechanics.

## Fracture mechanics

Stress intensity factor, K,
is parameter represented
intensity of stress distribution around crack.

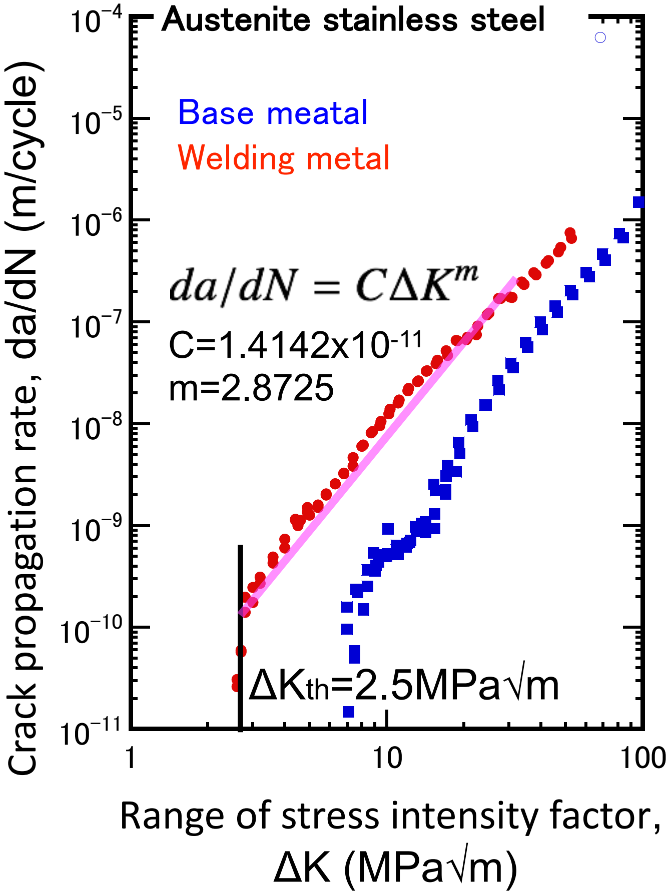



Cyclic load

$$\Delta K = F\Delta\sigma\sqrt{\pi a}$$

*a* : Crack length
σ : Stress calculated in num. simulation
$\Delta\sigma = \sigma_{max} - \sigma_{min}$

**$\Delta K > \Delta K_{th}$ : Fatigue crack propagation**




Fatigue data sheet made by
National Research Institute for Metals