# Mechanical Strength Evaluation of Superconducting Magnet Structures by HIP Bonding Method

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# Outline

1. Introduction
   - About Radial Plates
   - HIP method merits
   - Purpose of the study
2. Investigation of bonding temperatures
   - Materials and methods
   - Results and summary
3. Manufacturing of a full-sized mock-up
   - Manufacturing flow
   - Qualification test results
4. Conclusion

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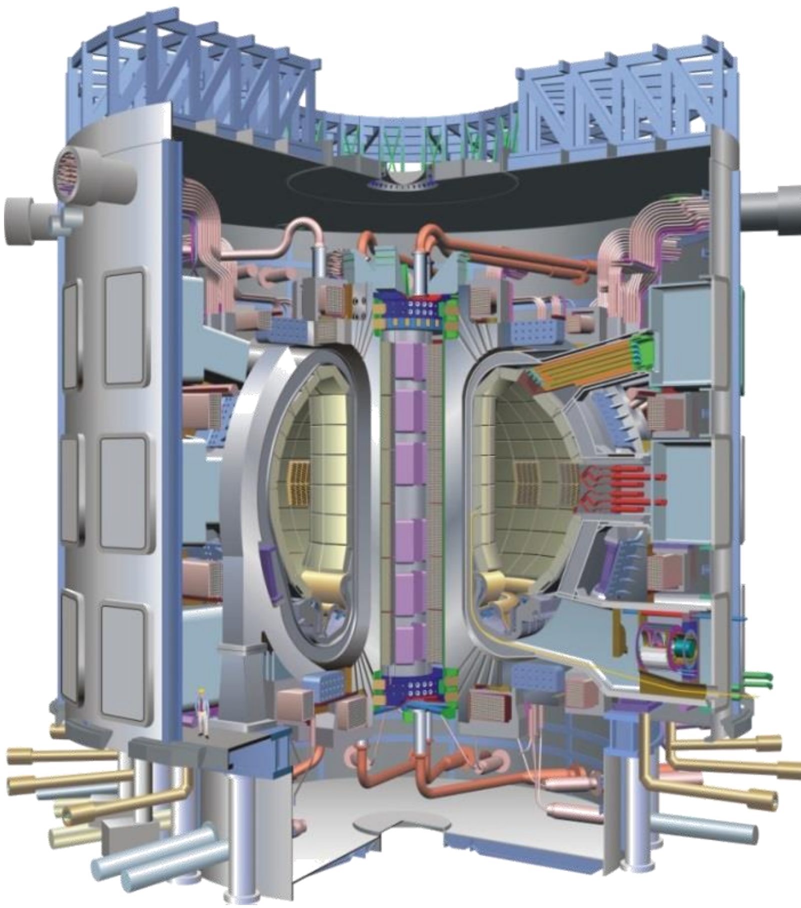
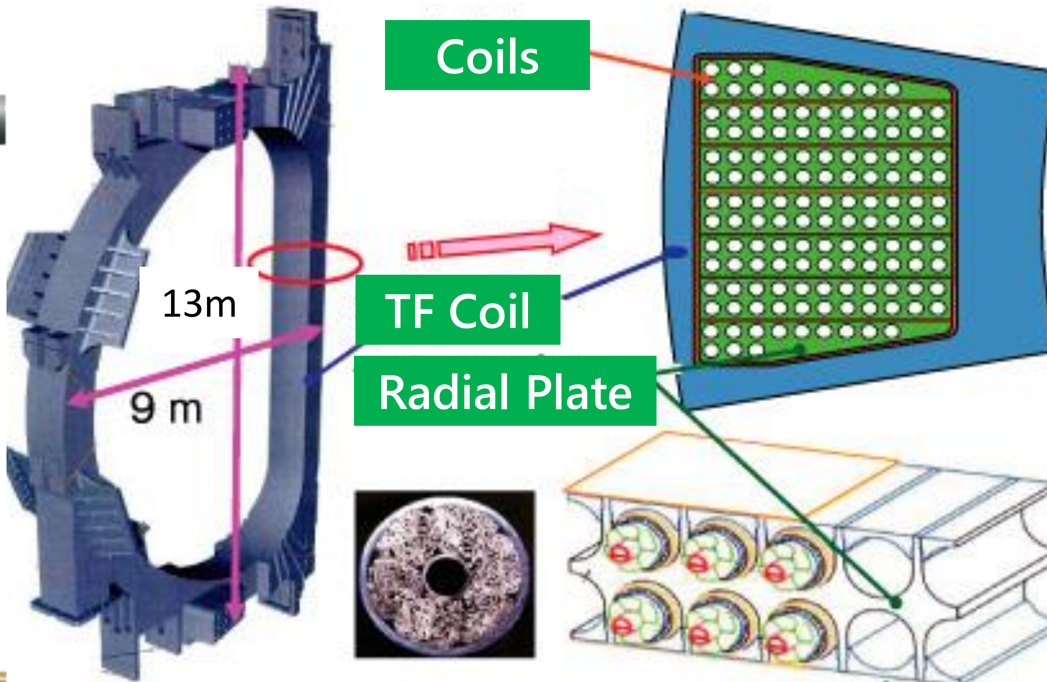
# Introduction- Radial Plates

The support structure of a Super-Electromagnetic Coil of ITER



ITER



# Introduction- Radial Plates

Table.1 Chemical composition of FM316LNH
(based on austenitic steel 316LN)

| Material | C | Si | Mn | P | S |
|---|---|---|---|---|---|
| Mass % | 0.03 max. | 2.00 max. | 2.0 max. | 0.035 max. | 0.02 max. |
| Material | Ni | Cr | Mo | N | C+N |
| Mass % | 10.0 -14.0 | 16.0 -18.5 | 2.0 -3.0 | 0.15 -0.20 | 0.18 Min |

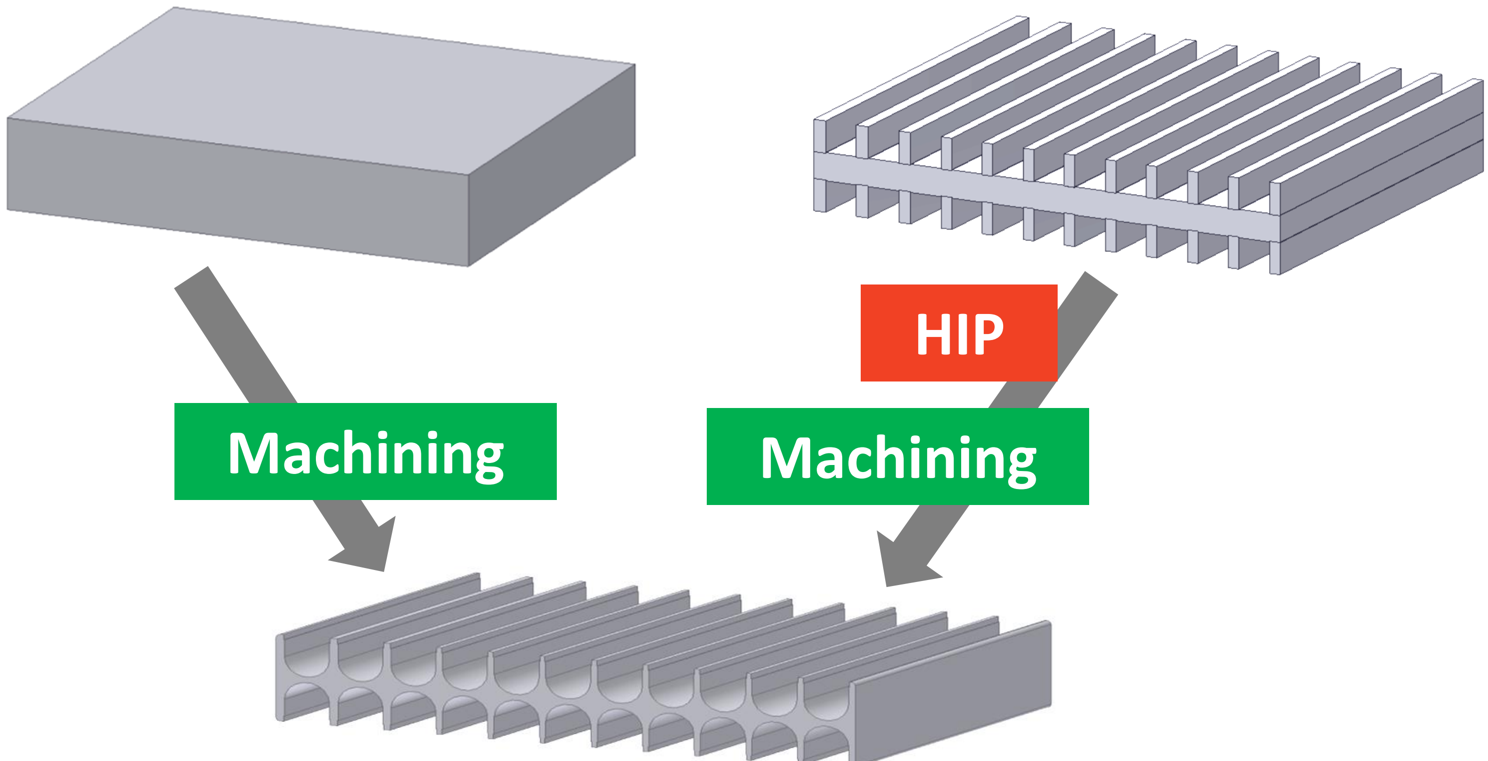
**FM316LNH requires:**

- **Purity raw materials**
- **Advanced forging technology**

**= High material cost**

# Introduction- HIP method merits

| Conventional method | HIP method |
|---|---|




**Material Yield 20%**

**Material Yield 67%**
**Material Mass 50%**
**Mechanical Properties ↓**

# Introduction- Purpose of the study

## 1: Investigation of bonding conditions with HIP temperatures.

**Goal: The base material & the bonded sections satisfy the design strengths.**

Table. 2 Mechanical properties of FM316LNH (Thickness<200mm)

| | Design Yield Strength(MPa) | | | Charpy Absorbed Energy(J) | Fracture Toughness $K_{IC}$ (Mpa・ √m) |
|---|---|---|---|---|---|
| Test Temperature | RT | 77K | 4K | 77K | 4K |
| Material Specified Value | 280 | 705 | 900 | 272* | 255* |

*Reference design values, and not required values

## 2: Produce RP segment mock-up by HIP method.

**Goal: Obtain uniform quality throughout the large structure**

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# Investigation of bonding temperatures

## 1. HIP treatment

**X ℃ × 118 MPa × 4 hrs.**

**X = 1050, 1100, 1150, 1200, 1250, 1300**

Table. 3 Chemical composition of test piece material

| Material | C | Si | Mn | P | S |
|---|---|---|---|---|---|
| Mass % | 0.024 | 0.54 | 1.53 | 0.018 | 0.0003 |
| Material | Ni | Cr | Mo | N | C+N |
| Mass % | 12.95 | 16.48 | 2.54 | 0.172 | 0.196 |

## 2. Material & Method

### B: Bonded Test Block

### M: Base material Test Block

Table. 4 Test Methods

| Test Item | Condition | Section | QTY. |
|---|---|---|---|
| Grain Size | Arbitrary | M | 1 |
| Bonded Interface | Arbitrary | B | 6 |
| Yield Strength | RT,77K,4K | M,B | 2 |
| Charpy Absorbed Energy | RT,77K | M,B | 3 |
| Fracture Toughness $K_{IC}$ | 4K | M,B | 2 |

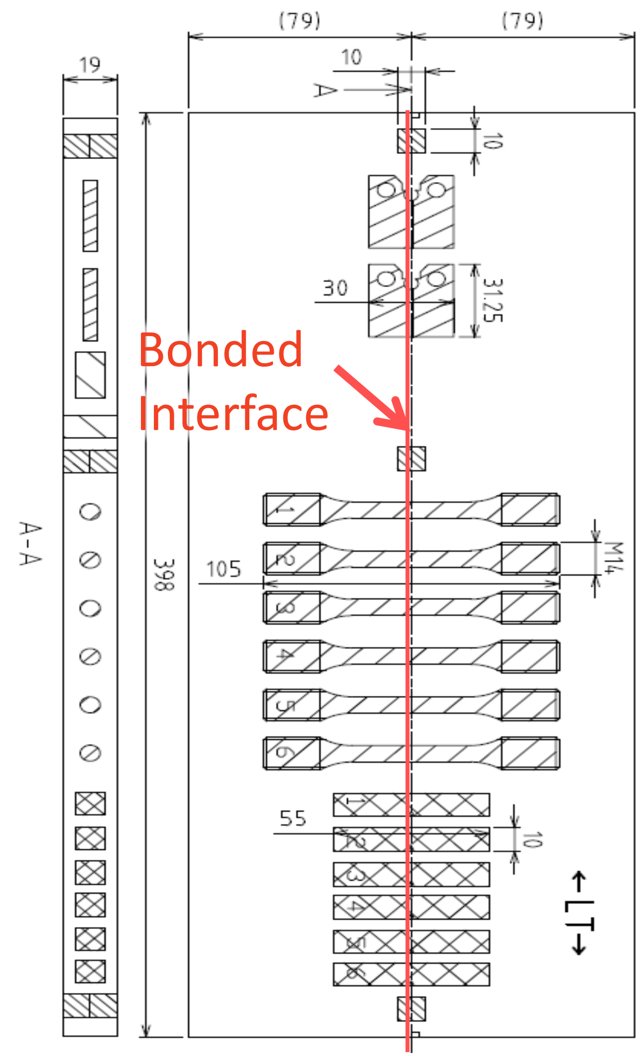


Fig.1 Bonded Test Block

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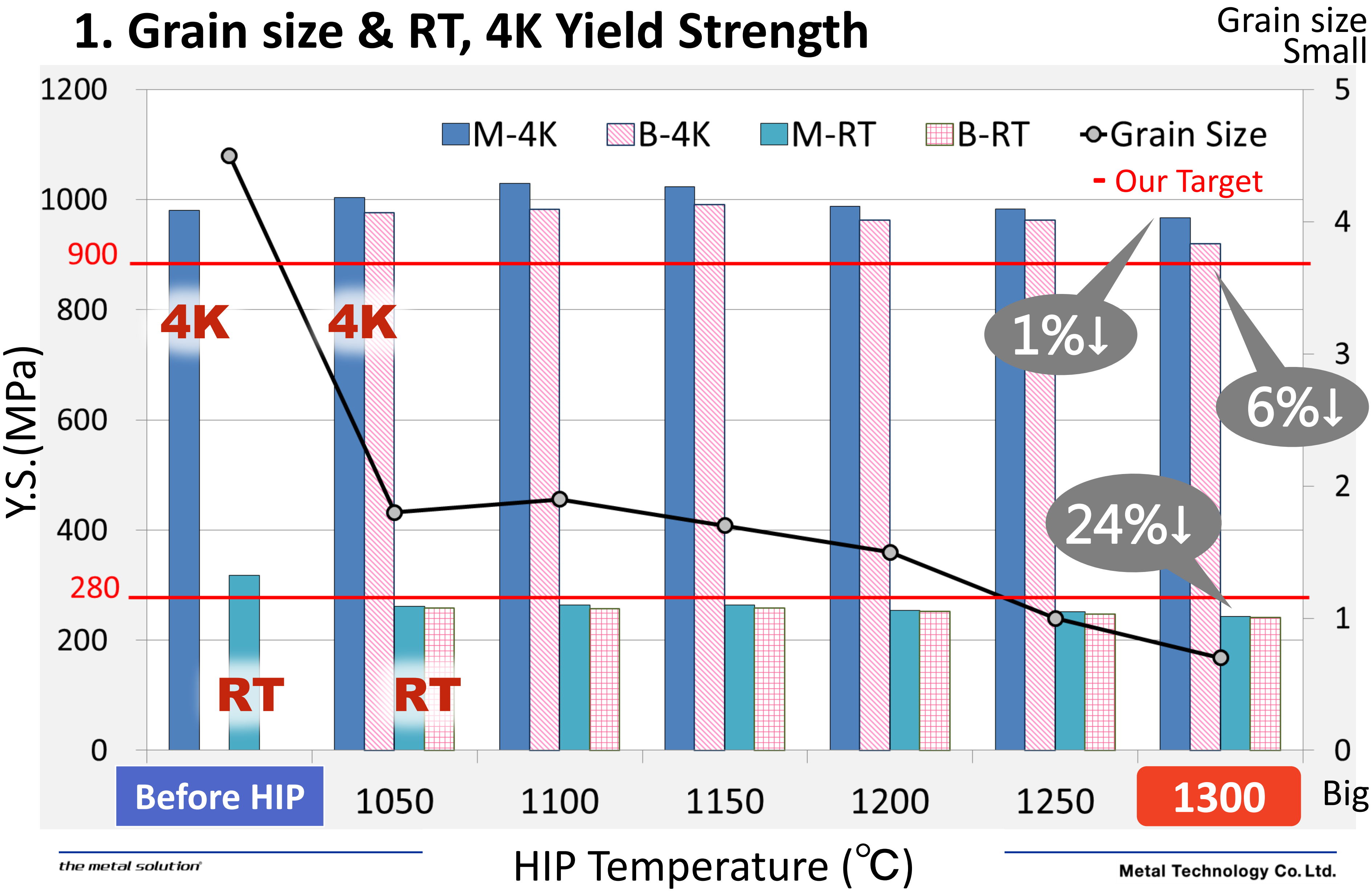
# Investigation of bonding temperatures

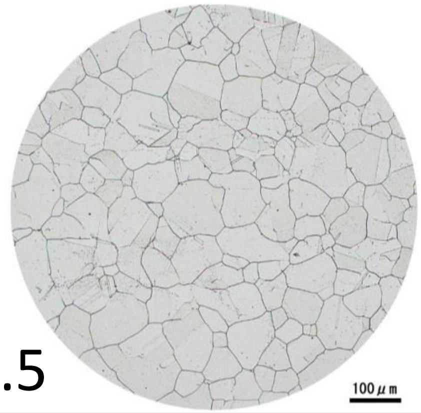
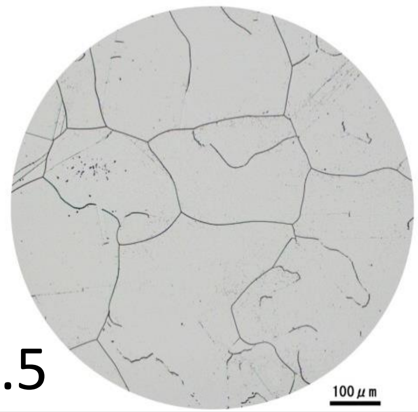
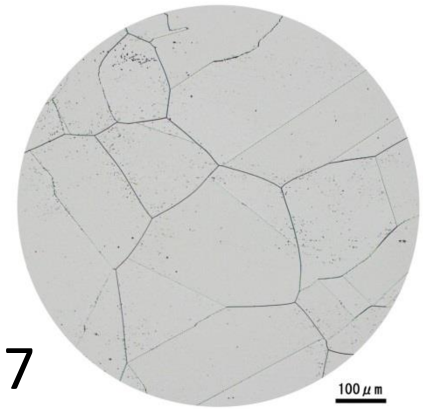
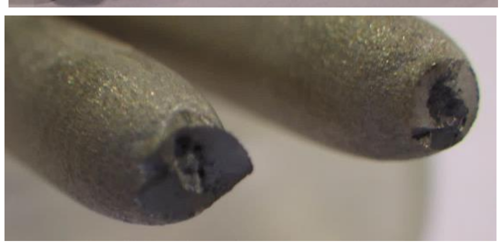
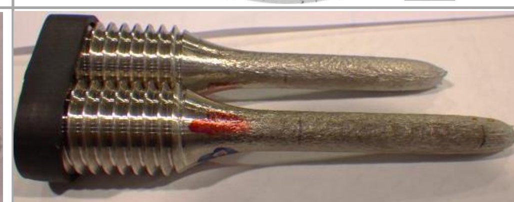
## 1. Grain size & RT, 4K Yield Strength



# Investigation of bonding temperatures

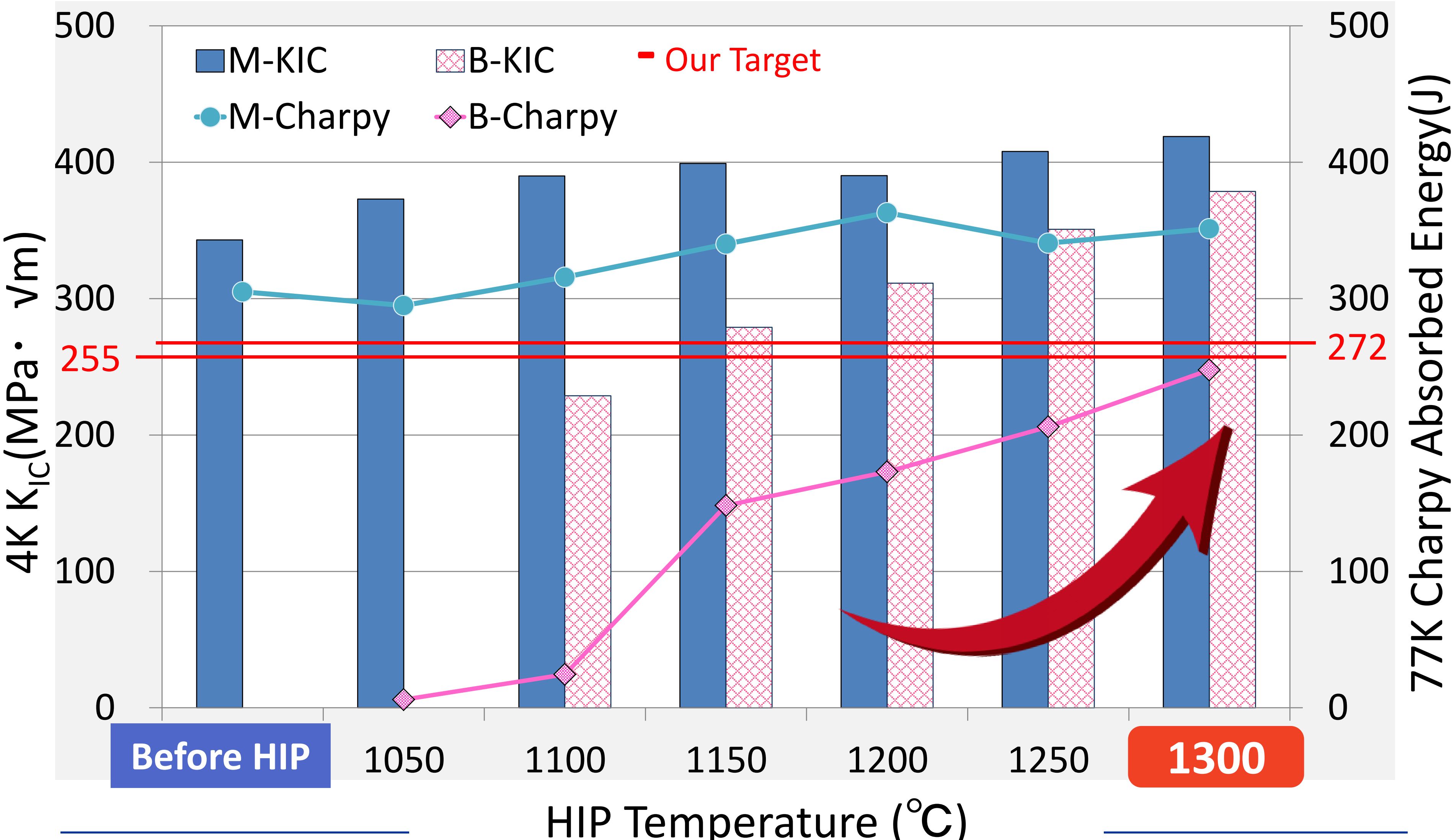
## 1. Grain size & RT, 4K Yield Strength

Table. 5 Grain size and fracture surface

| Temp. | Before HIP | 1200℃ HIP | 1300℃ HIP |
|---|---|---|---|
| Crystal Grains | 4.5  | 1.5  | 0.7  |
| Section M Tensile Fracture Surface at RT |   |   |   |
| | 318.1MPa | 253.6MPa | 243.3MPa |

# Investigation of bonding temperatures

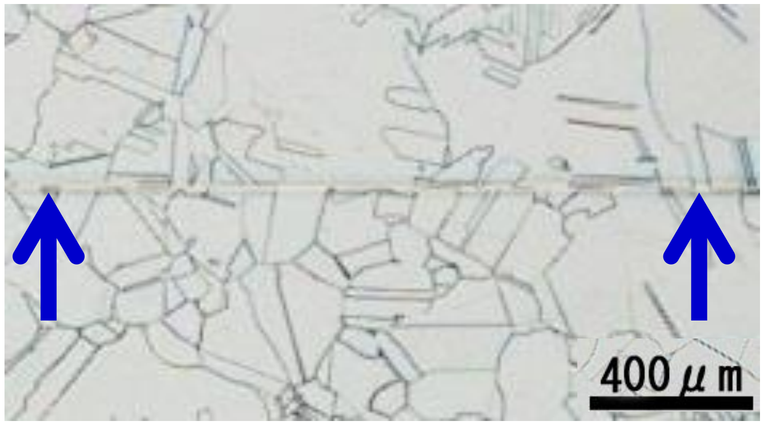
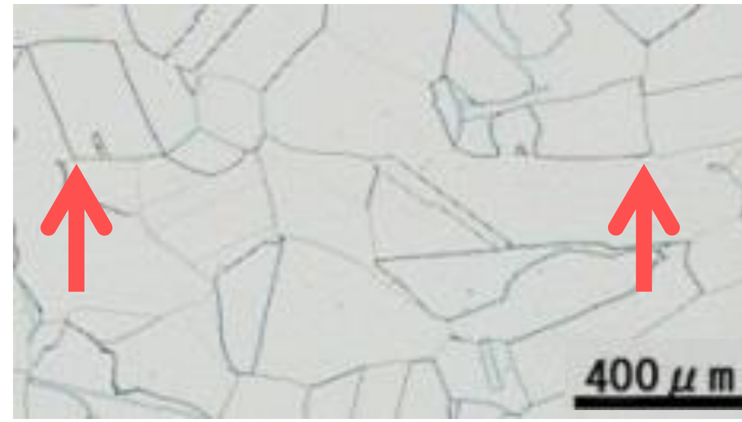
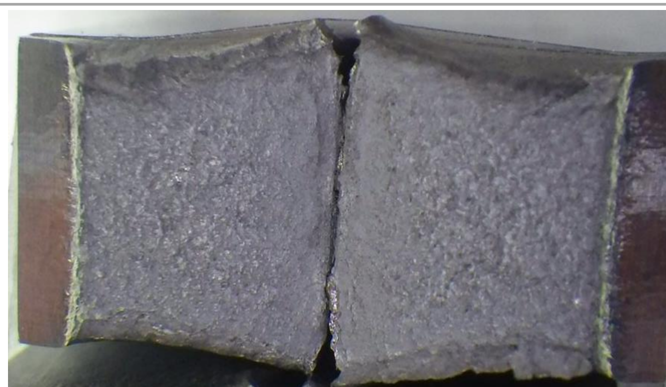
## 2. Fracture Toughness and Charpy Absorbed Energy



# Investigation of bonding temperatures

## 3. Bonding interface and fracture surface

Table.6 Bonded interface and fracture surface

| Temp. | 1200℃ | 1300℃ |
|---|---|---|
| Bonded Interface |   |   |
| Charpy Fracture Surface (77K) |  |  |
| | **Brittle** 173.0 J | **Ductile** 247.7 J |

# Investigation of bonding temperatures

## 1) Optimization of bonding temperature

**1300℃ provides the best achievable mechanical strength and toughness at 4K.**

## 2) Reduction of the yield strength

**At 1300℃ HIP treatment, the strength is reduced by 24% at RT compared with before HIP.**

**It is necessary to design for strength keeping in mind the reduction of the yield strength**

## 3) Full-seized product mock-up

**1300℃ × 4 hrs. × 118 MPa**

**Confirmed HIP can obtain consistent quality in a full-size structure.**

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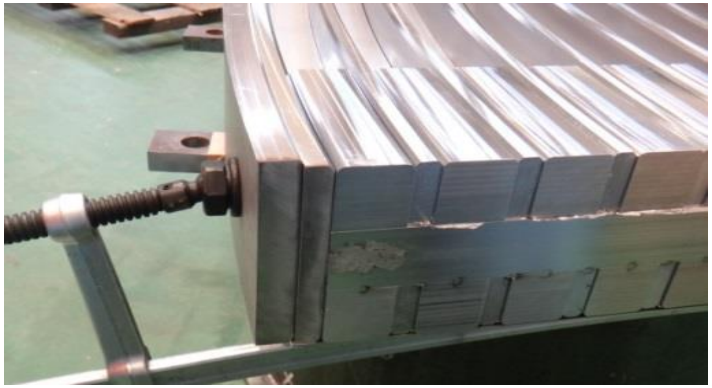
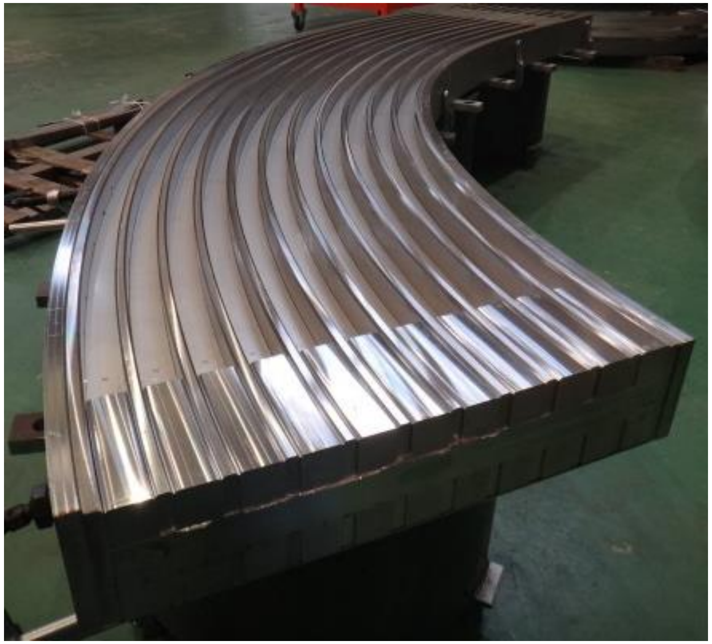
# Manufacturing of full-size mock-up

## Flow 1. Assembly Capsuling





**Work size:**
**1.1m x 2.6m x 135mm**

# Manufacturing of full-size mock-up

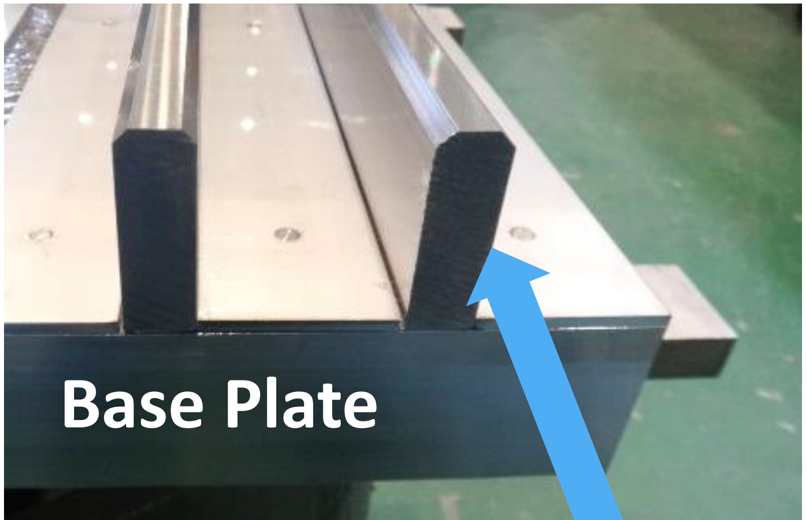
## Flow 2. HIP using Giga-HIP

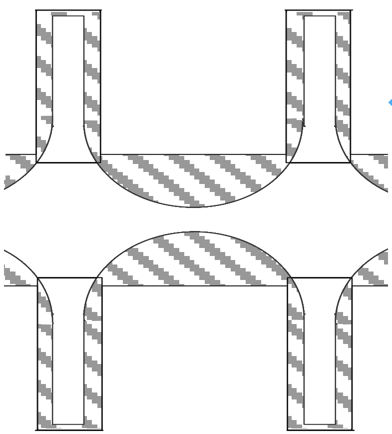
### HIP conditions: 1300 ℃ x 118 MPa x 4 hrs.

**Giga-HIP:**
**Working Zone: Φ2.05m x 4.2m**
**Max temperature: 1300℃**
**Max pressure: 118MPa**
**Max weight: 25,000kg**

# Manufacturing of full-size mock-up

## Flow 3. Machining



Flat bars

Base Plate

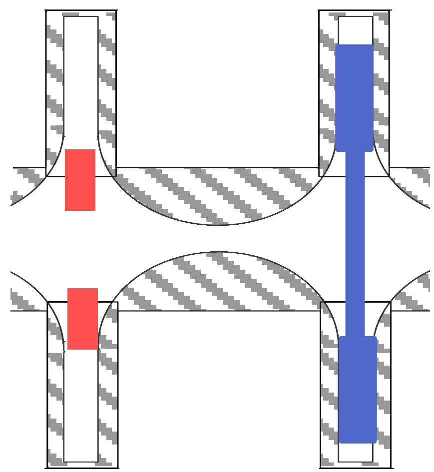
Machined area

# Manufacturing of full-size mock-up

## Flow 4. Removing Test Pieces

Table. 7 Test Contents

| Test Detail | Condition | QTY./area |
|---|---|---|
| Bonded Interface | Arbitrary | 26 |
| Yield Strength | RT, 77K, 4K | 6 |
| Fracture Toughness $K_{IC}$ | 4K | 8 |



Machined area

Yield Strength

Fracture Toughness $K_{IC}$

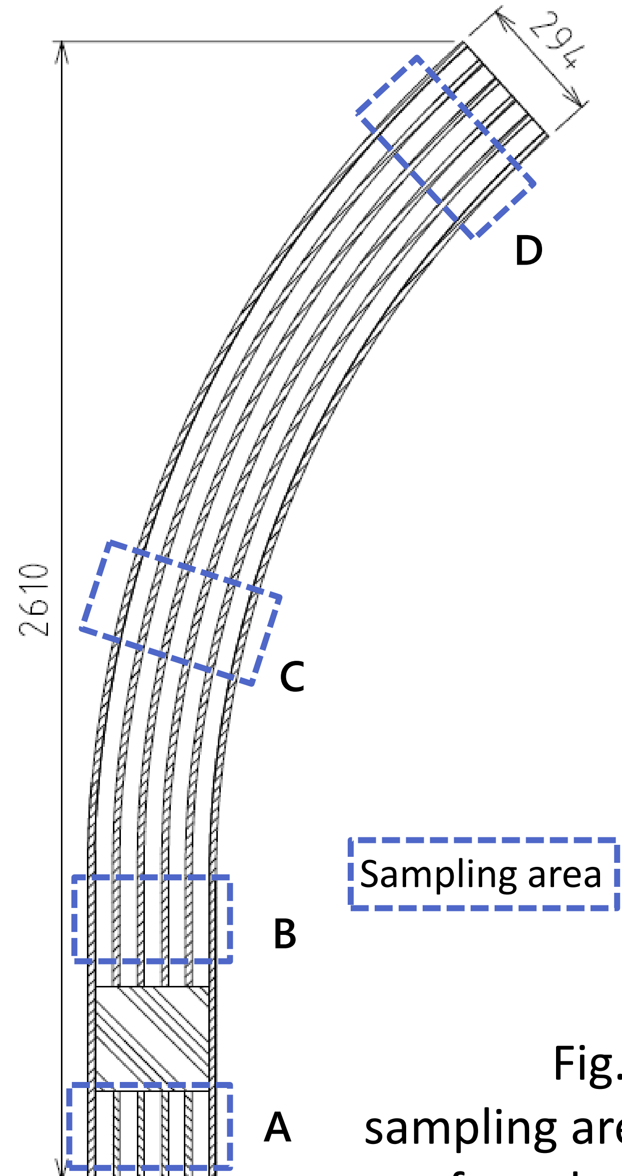



Fig. 2 sampling area of mock-up

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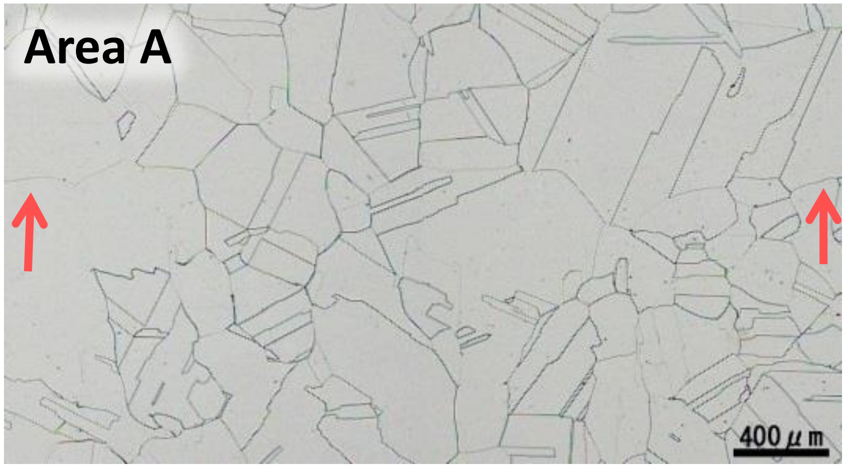
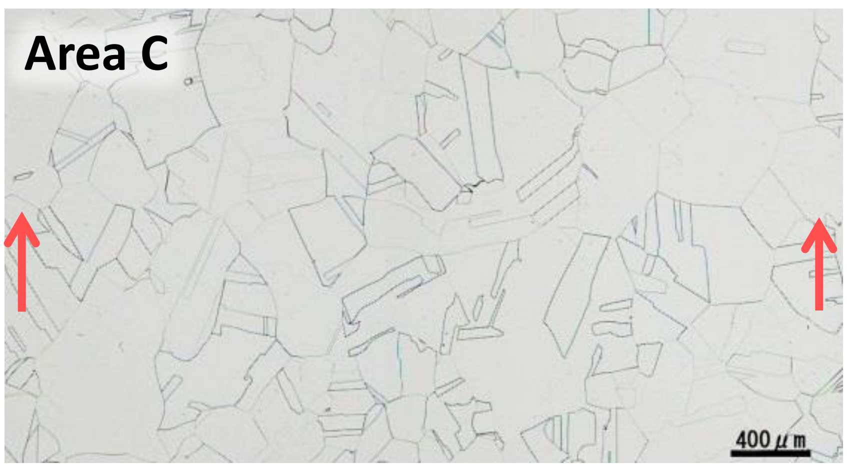
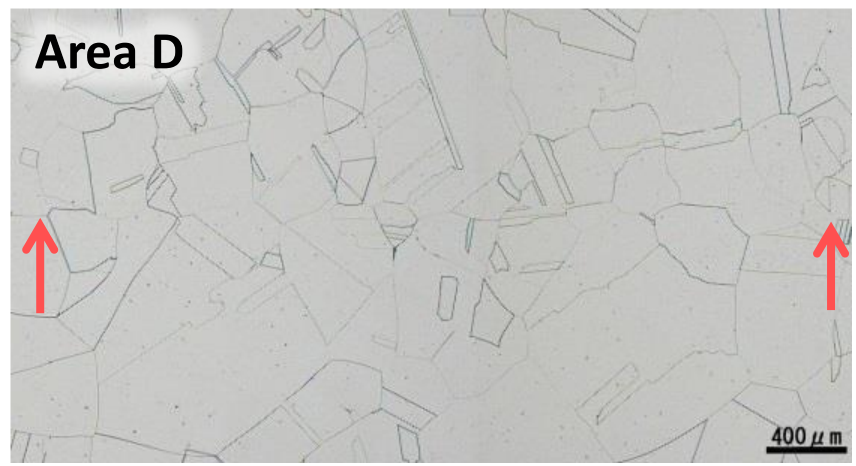
# Manufacturing of full-size mock-up

## 1. Bonded Interface








**The Bonded interfaces disappeared.**

# Manufacturing of full-size mock-up

MTC

## 2. Mechanical Strength and toughness

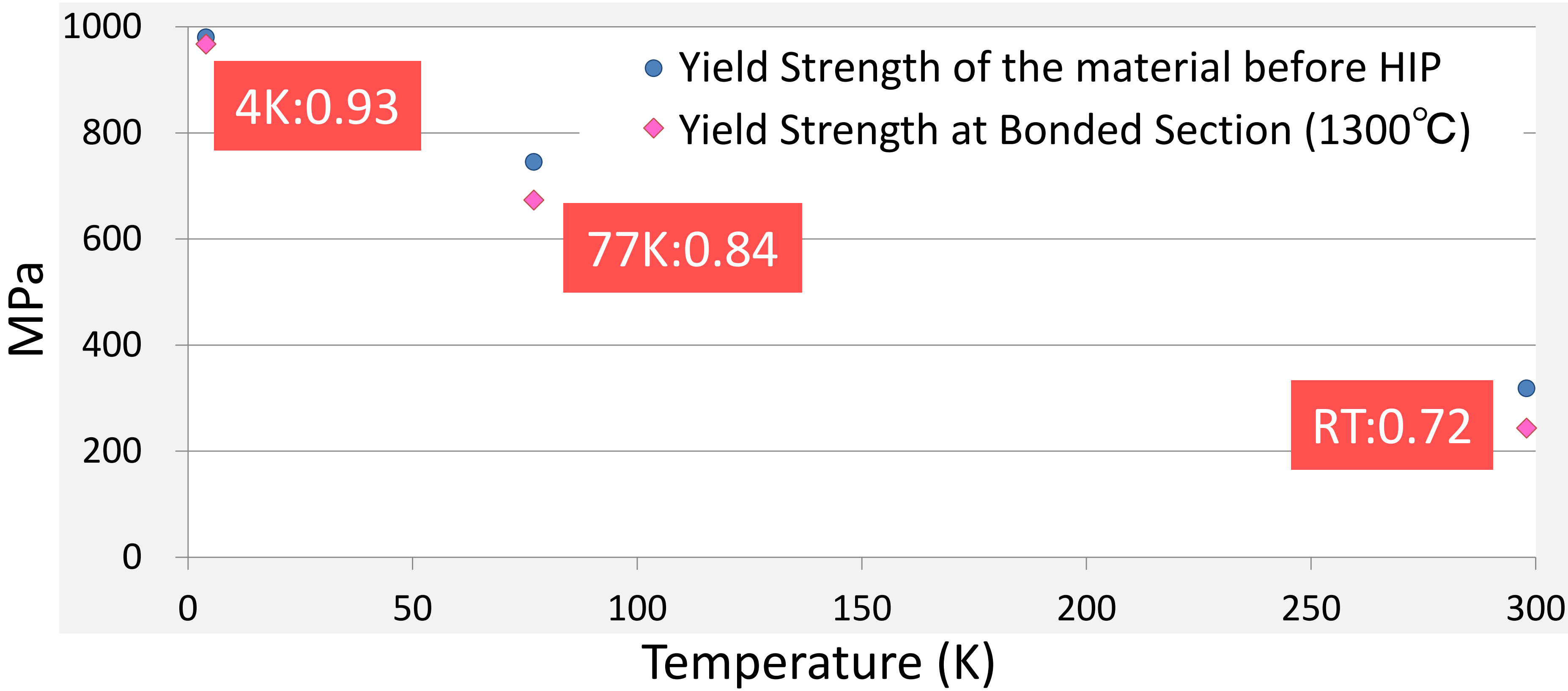
Table. 8 Mechanical Properties of Mock-up's bonded part (average value)

| Reference | Sample | Yield Strength (MPa) | | | Fracture Toughness $K_{IC}$ 4K (MPa・√m) |
|---|---|---|---|---|---|
| | | RT | 77K | 4K | |
| Section 1 | Specified value | 280 | 705 | 900 | 180* |
| Small Test Piece Section 2 | Martial before HIP | 318 | 745 | 976 | 343 |
| | Base material 【M】 | 243 | 673 | 967 | 419 |
| | Bonded part 【B】 | 241 | 660 | 920 | 379 |
| Full-size Mock-up Section 3 | Area A | 238 | 645 | 932 | 289 |
| | Area B | 237 | 647 | 932 | 326 |
| | Area C | 236 | 644 | 932 | 332 |
| | Area D | 233 | 635 | 919 | 334 |

**Uniformed quality can be obtained regardless of the product size.**

# Manufacturing of full-size mock-up

## 3. Reduction Factor

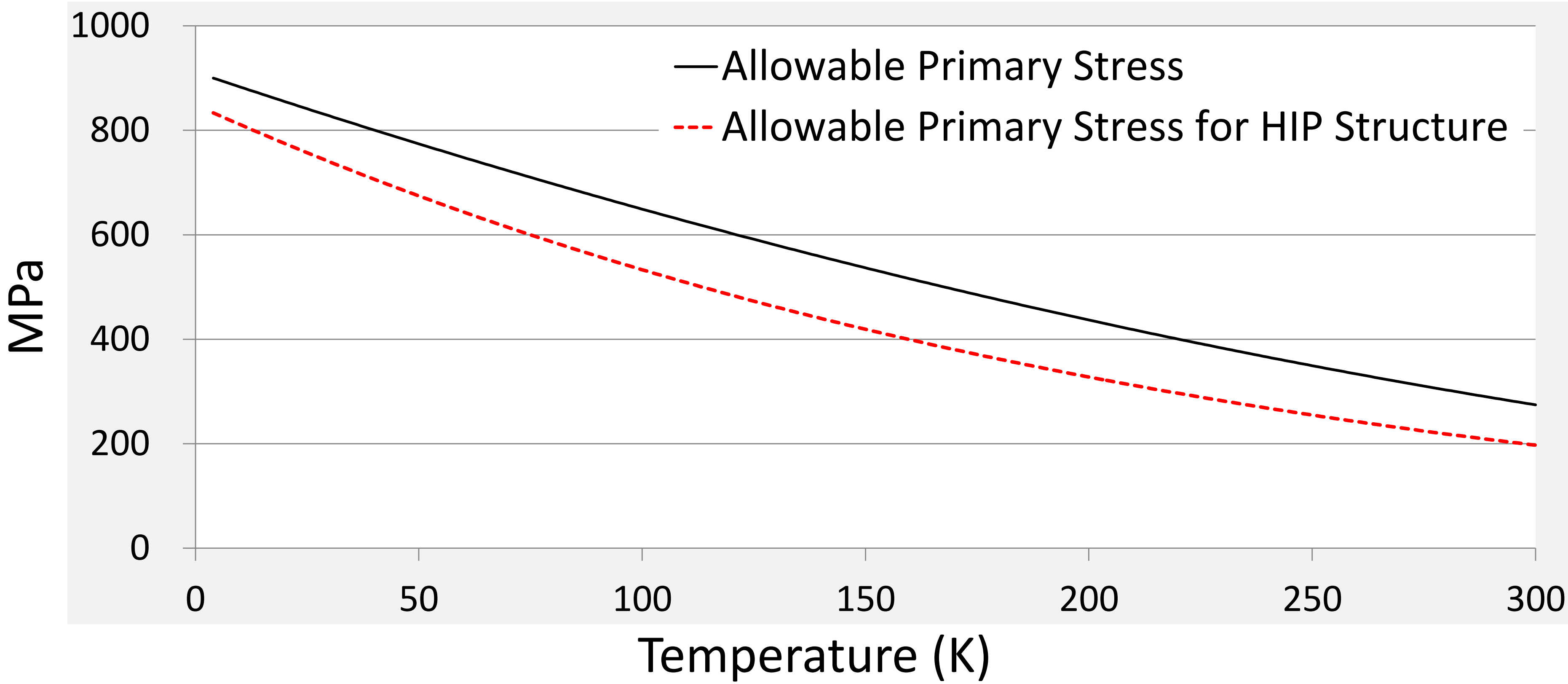



**Reduction Factor given by;**

$$1.955 \times 10^{-6} \times T^2 - 1.295 \times 10^{-3} \times T + 0.9311$$

*T=temperature (K)*

## 3. Reduction Factor




**The Allowable Stress can be corrected using the Reduction Factor.**

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# Conclusion

## 1: Investigation of bonding condition with HIP temperatures.

1300℃ provides the best achievable mechanical strength at 4K.

## 2: Produce a Radial Plate segment mock-up using HIP.

Uniformed bonding was obtained regardless of the size and structure of the HIP bonded parts.

## 3: Necessity to consider the strength reduction.

The allowable stress intensity can be corrected using the Reduction Factor.

# Future considerations

**Collecting fatigue data at the bonded sections according to operating conditions to obtain the Fatigue Strength Reduction Factor**

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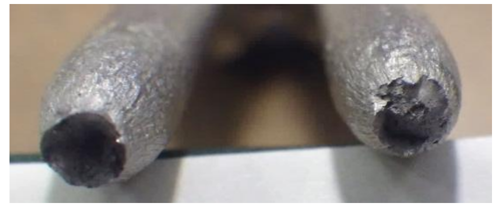
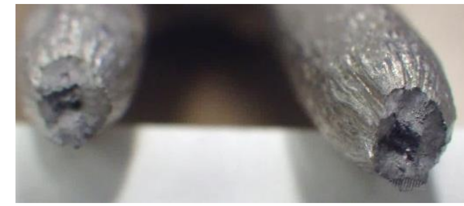
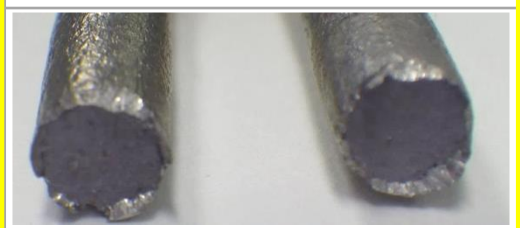
# Investigation of bonding temperatures

## Bonded section's Yield strength

| Temp. | 1100℃ HIP | 1200℃ HIP | 1300℃ HIP |
|---|---|---|---|
| RT | <br>257.3 MPa | <br>251.7 MPa | <br>241.4 MPa |
| 77K | <br>700.3 MPa | <br>691.7 MPa | <br>659.9 MPa |
| 4K | <br>982.3 MPa | <br>962.0 MPa | <br>919.6 MPa |

Coarsening of the crystal grains due to heat input influences the reduction of Yield Strength

# Reduction factor

| Test Temperature | RT | 77K | 4K |
|---|---|---|---|
| Average Value | 0.742 | 0.862 | 0.948 |
| Standard Deviation(σ) | 0.010 | 0.008 | 0.009 |
| Reliability of 99%(2.33σ) | 0.023 | 0.019 | 0.022 |
| Reduction | 0.719 | 0.843 | 0.926 |

**Reduction Factor given by;**

$$1.955 \times 10^{-6} \times T^2 - 1.295 \times 10^{-3} \times T + 0.9311$$

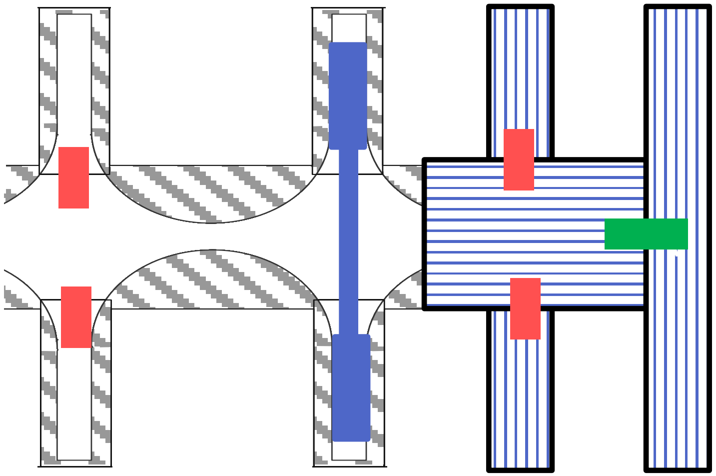
JSME Construction Standard for Superconducting Magnets of Fusion Facilities

# Chemical Composition

Changing Chemical Composition of the base material

| Material | | C | Si | Mn | P | S |
|---|---|---|---|---|---|---|
| Mass | Pre-HIP | 0.024 | 0.54 | 1.53 | 0.018 | 0.0003 |
| % | After | 0.023 | 0.57 | 1.50 | 0.021 | <0.001 |
| **Material** | | **Ni** | **Cr** | **Mo** | **N** | **C+N** |
| Mass | Pre-HIP | 12.95 | 16.48 | 2.54 | 0.172 | 0.196 |
| % | After | 13.11 | 16.43 | 2.50 | 0.167 | 0.190 |

# Manufacturing of full-size mock-up



The weakest test piece