Mechanical Compress Process for Pre-compression of JT-60SA Central Solenoid

Haruyuki Murakami, Katsuhiko Tsuchiya, Kaname Kizu, Kazuya Hamada (QST)
Kazuhiro Nomoto, Itashiki Yutaro(Mitsubishi Electric Corporation)

23 Sep 2019, Vancouver, Canada
1. Operation Condition
Current: 20 kA, $B_{\text{max}}$: 8.9 T

- Nb$_3$Sn Cable
- Jacket (SS316LN)

2. Magnet Design
- CS system has 4 modules.
- Each module consists of 52 layers
  - 6 Octa-Pancake (OP: 8 layer)
  - 1 Quad-Pancake (QP: 4 layer)
- Conductors are electrically insulated by GKG (Glass-Kapton-Glass) tape with epoxy resin. ($V_{\text{layer}} = 1.8$ kV)
- Half lap x 2 times (416 tapes/module)

Total thickness of insulation (GKG tape) is more than 300 mm for 4 modules
CS Precompress

Stacked 4 CS modules need to be fixed each other by 9 sets of tie plate (SS316LN) with large compress load.

Compress load
- Sufficient compress load, considering cool down and operation, need to be subjected to modules.
- The compress load had been estimated by FEM analysis.
  - Inner: 2.11 MN ± 10%
  - Outer: 2.05 MN ± 10%
  - Total: More than 4.16 MN for each tie plate.
(There are 9 sets of tie plate in total)

Main topic of this presentation
How to conduct precompress actually.
- Design of compress jigs
- Analysis of compress jigs
- Procedure and measurement of precompress
- Result of precompress
Precompress load

**Compress load is reduced by cool down**
- Compress load is reduced during operation (Contact area is more than 50% in any case)

### Temperature vs. Electromagnetic Force

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Electromagnetic force</th>
<th>Axial force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tie plate</td>
</tr>
<tr>
<td>RT</td>
<td>---</td>
<td>Inner MN</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Outer MN</td>
</tr>
<tr>
<td>4K</td>
<td>---</td>
<td>Repulsion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Attraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Repulsion EMF**: Minimum axial force is between CS2 and CS3
- **Attraction EMF**: Minimum axial force is bottom of CS modules

---

- **Thermal shrinkage**: Module > Tieplate (SS) → Compress load is reduced

---

- **Tie Plate**: 2.11 MN × 9 tieplates
- **Module**: 2.05 MN × 9 tieplates
Design of precompress jigs

**<Precompress method>**
- **Shrink fit by using heaters (80°C heating is estimated to get sufficient load)**
  Simple jigs and simple procedure $\leftrightarrow$ Difficult to adjust precompress load after setting.
- **Mechanical pulling by jacks**
  Large jigs and complex procedure $\leftrightarrow$ Easy to adjust precompress load after setting.

Creeping amount of thick insulation is unknown

Mechanical loading process was selected

$\rightarrow$ We can retighten after creeping
Analysis model for jigs

Precompress jigs are validated by analysis considering plastic deformation.

The number of applied load is only a few times for initial precompress and retightening (if needed).

The structures have been validated by analysis considering repeated load based on JSME code.

(Cool down : 100 times, Operation load : 36,000 times)

Analysis model for jigs

<Analysis model>
- Module, tieplate and jigs are modeled.
- 40 degree symmetrical model

<Boundary condition>
① Bottom surface of jack is fixed.
② Side surface is symmetrical condition.

<Load condition>
A. Vertical load is applied to upper surface of jack.
   → Applied load is up to 160% of rated value.
B. Bolts of jigs are tightened by rated value of class 8.8 bolt.
C. Bolts of jigs are tightened by 10% of rated value of class 8.8 bolt.
   → Tieplate need to be slided.
<Contact condition>

a. Contact surface of tieplate and key block
b. Contact surface of tieplate and jigs

→ These surface have 0.2 of coefficient of friction.
→ All other surfaces are bonded condition.
Stress-strain curve

Structure become broken at Strain > Ultimate strain
(SCM440H:7.4%, SS316LNM:16.0%)

Precompress jig (SCM440H)
↑Cr–Mo alloy steel

Tie plate (SS316LNM)

(7.4%, 980MPa)
(4.175%, 835MPa)
(16.0%, 550MPa)
(0.2%, 245MPa)
<Analysis Result> (Rated load : 4.16 MN)

- Strain is less than ultimate strain even under the load condition as 160% of rated load.
- Plastic deformation occurs in very local area.

→ Jigs can be used in safe

Arms of jigs tend to open.
→ 1~2 degree under 120% of rated load.
→ Opening prevention plate is added for actual precompress jigs to reduce plastic deformation.

\[
\text{Inner: } 1.9^\circ \\
\text{Outer: } 1.1^\circ 
\]
Analysis Result (Strain)

Precompress jig (Ultimate strain : 7.4%)

- Inner:
  - 100%: 1.7%
  - 120%: 2.7%
  - 160%: 5.5%

Blue area = Elastic area

Maximum strain

- Outer:
  - 100%: 1.1%
  - 120%: 1.7%
  - 160%: 5.7%

Tie plate (Ultimate strain : 16.0%)

- Inner:
  - 100%: 6.2%
  - 120%: 7.8%
  - 160%: 12.6%

Blue area = Elastic area

Maximum strain

- Outer:
  - 100%: 3.0%
  - 120%: 4.1%
  - 160%: 8.0%

Maximum strain is less than ultimate strain up to 160% load
Precompress procedure

<Setting Jigs>
- Hydraulic jack and pump is separately installed to each sector to control precompress load individually.
- Strain gauges are attached to both surface of tie plate.
- Precompress load is evaluated by the measured tie plate strain and Young’s modulus of 200GPa.
- Opening prevention plate is added for actual jigs.

<Procedure>
- Precompress load is gradually increased. (e.g. 20%→50%→80%→90% of target load)
- Check the proportionality of precompress load and hydraulic pressure (Plastic deformation)
- Adjust insertion shims by 0.1 mm thickness to get target load after unloading of hydraulic jack.
- Holding load for a night after loading.

<table>
<thead>
<tr>
<th></th>
<th>Target</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner</td>
<td>1.90～2.33MN</td>
<td>2.00～2.27MN</td>
</tr>
<tr>
<td>Outer</td>
<td>1.85～2.26MN</td>
<td>2.05～2.25MN</td>
</tr>
<tr>
<td>Total</td>
<td>More than 4.17MN</td>
<td>4.25～4.35MN</td>
</tr>
</tbody>
</table>
Retightening can be conducted until finish of creeping by using mechanical loading method.

**Result of precompress**

**Inner:** 1.90～2.33 MN

- Hold for a night
- Hold for 2 hours
- Add Shim

**Outer:** 1.85～2.26 MN

- Hold for a night
- Hold for 2 hours
- Add Shim

**Total:** more than 4.17 MN

- Hold precompress load for a night after first loading
  → Load changes by insulation creeping.
  → Amount of change differ from sector to sector.
- Additional shims were inserted for small load sector.
- Hold for 2 hours to check no additional creeping.

Precompress was successfully performed.
Summary

1) The mechanical loading technology has been developed for CS precompress. It can adjust precompress load easily after tie plate setting.

2) Precompress jigs were designed by using plastic mechanical analysis.
   (a) Maximum strain is less than ultimate strain up to 160% load.
   (b) Arm of precompress jigs tend to open by 1~2° at 120% load.
      → Opening prevention plate is added to reduce plastic deformation.

3) Precompress was performed using developed jigs.
   (a) Hold precompress load for a night after first loading.
      → Precompress load changes by insulation creeping and amount of change differ from sector to sector.
      → Additional shims were inserted for small load sector.
   (b) Finally, precompress load of all tie plate is within target range.

Precompress was successfully performed using developed jigs