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MECHANICAL ANALYSIS AND TESTS OF AUSTENITIC STAINLESS STEEL BOLTS FOR BEAMLINE FLANGE CONNECTION

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Abstract

Cryogenic tests of 1.3 GHz superconducting accelerator cryomodule for the Shanghai Hard X-ray Free Electron Laser Installation Project (SHINE) are in progress. For better performance, a study of mechanical analysis and tests of austenitic stainless steel bolts for beamline flange connection has been done in preliminary work. In order to satisfy the residual magnetism and strength, high-strength austenitic stainless steel bolts are selected. For higher sealing performance, the torque coefficient is determined by compression test, the lower limit of yield of the bolts is obtained by tensile test, then the maximum torque applied to the bolts under real working conditions can be obtained according to the relationship between preload and torque. A finite element model is established to get the deformation curve of the gasket, and the measured results of gasket thickness are compared to ensure the reliability of the simulation. The deformation curve of the gasket is used to calculate the change of compression force under the temperature cycling load (cool down and warm-up). Finally, the results of residual magnetism show that the bolts have a negligible effect on magnetic field.

INTRODUCTION

1.3 GHz superconducting accelerator is characterized by extremely good vacuum condition [1-3]. Many of the flanges that are along the beamline immersed in the insulation vacuum. The connection construction is shown in Figure 1, which has to guarantee a reliable sealing performance both at room and cryogenic temperature, also after warm-up.

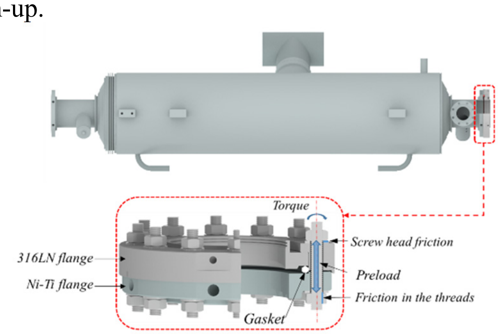

Figure 1: Beamline flange connection.

The mechanical properties, the applied torque, the preload changes with temperature of the bolts, etc., all affect sealing quality.

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TENSILE TEST

For the requirement of the residual magnetism and higher fracture toughness at cryogenic temperature, 316LN high-strength bolts are selected. The mechanical properties of the bolts prepared by a domestic and a foreign company respectively have been tested at room temperature. The size [4] of the tensile samples is shown in Figure 2. Four samples are tested and the average value is used for discussion.

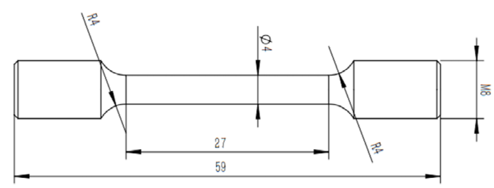

Figure 2: Sampling map.

All samples are tested for mechanical properties at room temperatures. The engineering stress-strain curves of some tensile samples are shown in Figure 3.

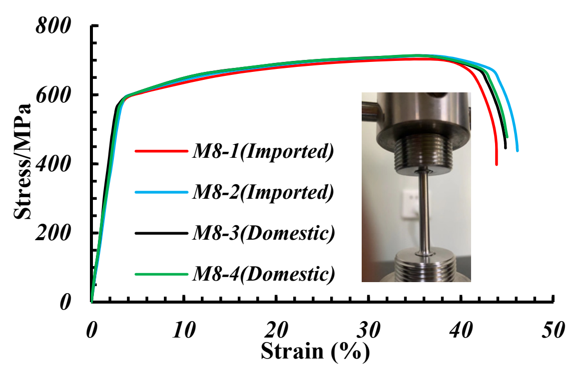

Figure 3: Engineering stress-strain curves of the samples.

The results including R_{el} (Lower limit of yield), UTS (Ultimate tensile strength) and EL (Elongation), are shown in Table 1. From Table 1, it can be seen that the average R_{el} of the bolts is 595 MPa, and the EL is greater than 40 %.

Table 1: Tensile Test Results at Room Temperature

Coding	R_{el} *MPa*	UTS *MPa*	EL *%*
Imported-1	598	711	44
Imported-2	596	710	46
Domestic-3	586	704	45
Domestic-4	603	712	45

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MEASUREMENT OF TORQUE COEFFICIENT

Given the mechanical properties of the bolts, the torque coefficient is measured to determine the maximum torque that could be applied. A representation of the experimental apparatus is shown in Figure 4. A ring force sensor with a precision of 1% has been used for the compression test. The upper and lower flanges made by 316LN and niobium-titanium respectively are used to simulate the demountable connection.

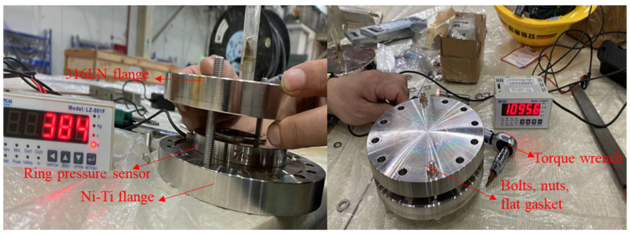

Figure 4: Presentation of the experimental apparatus.

According to the mechanical design manual:

$$T = FKd \quad (1)$$

$$K = \frac{d_2}{2d}\tan(\emptyset + \rho_v) + \frac{\mu}{3d} \times \frac{D_W^3 - d_0^3}{D_W^2 - d_0^2} \quad (2)$$

Where K is torque coefficient, F is clamp force, μ and $\boldsymbol{\rho_v}$ are friction factor, other parameters are bolt-related dimensions. Formula (2) shows when the bolt size is determined, K is effected by the friction coefficient, which can be measured by the compression test. Three sets of tests a carried out using the same batch of different M8 bolts with the same surface treatment. The test results are shown in Figure 5.

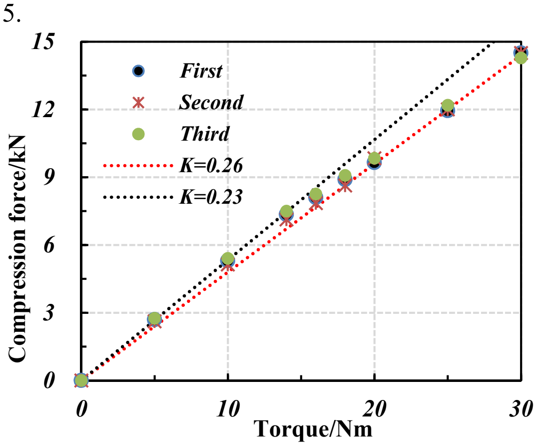

Figure 5: Relation between torque and compression force.

It can be seen that:

- Compression force and torque are basically linear. K spans a range from 0.23 to 0.26.
- K increases slightly with the torque, which may resulted by thread deformation.

Considering the combined effects of tension and torsion,

$$\frac{1.3F}{S} < \frac{R_{el}}{1.1} \quad (3)$$

Where S is stress cross section of the bolts, '1.1' is taken into account manual tightening torque deviation (The accuracy level of the torque wrench used is not lower than class 2 specified in JJG707-2003). So we got maximum torque:

$$T_{max} = 31.7 \text{ Nm}.$$

TEMPERATURE EFFECT ON COMPRESSION FORCE

Temperature change (cool down and warm-up) may induce additional deformations to the gasket and the bolts which may lead to leakage of the connection [5]. Therefore a finite element model has been developed to simulate the behaviour of the connection. The beamline connection simplified geometry is shown in Figure 6. The force-deformation curve is obtained by simulation shown in Figure 7.

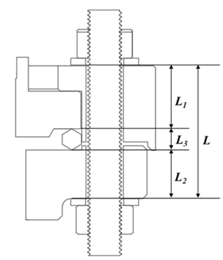

Figure 6: Simplified geometry of the beamline connection.

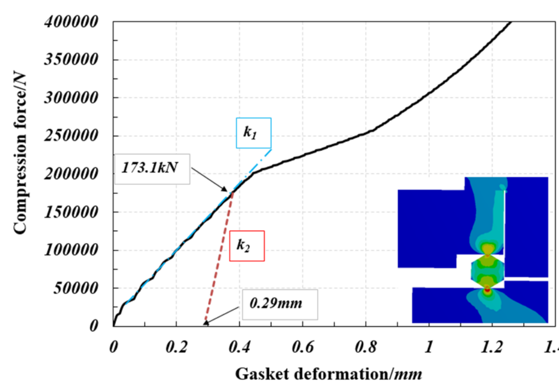

Figure 7: Force-deformation curve of the gasket.

A torque of 30 Nm is applied to each bolt to achieve a better sealing performance. According to Formula (1) and the torque coefficient measured in previous part, the compression force on the gasket is $F_c = Tn/Kd = 173.1$ kN.

When the compression force is completely released, the thickness of the gasket is reduced by 0.29 mm which is consistent with measurement shown in Figure 8.

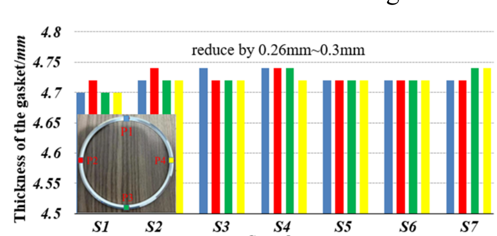

Figure 8: Thickness of the gaskets after applied 30 Nm.

In the cool down to the liquid helium temperature the difference of thermal elongation is

$$\Delta L_t = L\Delta T - L_1\Delta T_1 - L_2\Delta T - L_3\Delta T_3 = 0.00734 \text{ mm}$$

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That means the gasket will be further compressed and the preload of the bolts will increase. By the deformation relation,

$$\frac{\Delta F}{k_1} + \frac{\Delta F L}{nES} = \Delta L_t,$$

$\Delta \boldsymbol{F}$ increases by 2890 N. That is the axial force of a single bolt increases 241 N. Judging from Formula (3), the bolt is still elastic deformation.

When it returns to room temperature, as

$$\frac{\Delta F}{k_2} + \frac{\Delta F L}{nES} = \Delta L_t,$$

the preload of a single bolt decreased by 1077 N, which is a small value compared to the initial preload of 14423 N.

In conclusion, it can be seen that the change of compression force caused by temperature change is small, and will not affect the sealing performance of the beamline flange connection.

RESIDUAL MAGNETISM TEST

The beamline flange connection should not affect the magnetic field, and the residual magnetism of bolts is required to be less than 0.5 Gs. For higher reliability, the tightening torque of the M8 bolt is set to 30 Nm, which is very close to the torque that may result in plastic deformation of the bolt. Taking into account the error of artificial tightening force and the temperature change, 5 M8 bolts are selected for the remanence detection in factory state and plastic deformation state. Conservatively, the tightening torque of the bolts even reach 50 Nm. Whether the bolt has plastic deformation is determined by the length of the bolt before and after the torque is applied as shown in Figure 9. The test results of residual magnetism are shown in Figure 10.

Figure 9: Length measurement.

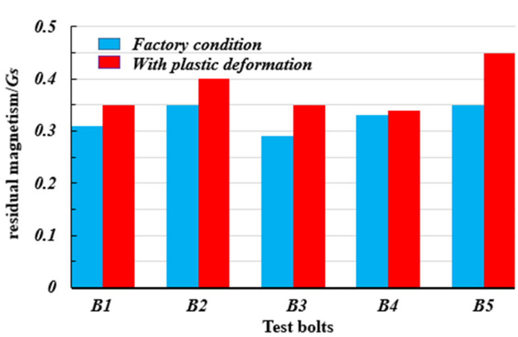

Figure 10: Residual magnetism of the bolts.

According to the results, when plastic deformation of the bolts occurs, the residual magnetism increases to a certain extent, but it still meets the requirement of less than 0.5 Gs.

CONCLUTIONS

A study on behaviours of the austenitic stainless steel bolts for 1.3 GHz superconducting cavities' beamline flange connection has been performed. The lower limit of yield and torque coefficient obtained by related tests are used to calculate maximum tightening torque. The results of finite element analysis, gasket thickness test and the change of compression force with temperature indicate that temperature cycle has little effect on the sealing performance of the beamline flange connection. The residual magnetism of the selected austenitic stainless steel bolts also meet the engineering requirement (less than 0.5 Gs). Subsequently, the allowable torque of bolts at the other connections can be determined in same way.

ACKNOWLEDGEMENTS

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