§2. On-site Winding of the Helical Coil for LHD

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Helical-coil winding machine was constructed at September, 1994. It is used for shaping helical-coil conductors with high accuracy and feeding continuously and smoothly without extra bending. The conductor shaping head includes three sets of shaping rolls. The conductors are in-plane bent, out-of-plane bent and twisted simultaneously by going through these rolls. Since the bending radius and torsion angle change complicatedly and continuously along the helical coil, driving axes for the winding machine are numerically controlled(NC). Including the axes for toroidal and poloidal rotation, the number of NC axes in the winding machine is 13: 7 axes are in the shaping head.

Before winding, the helical coil can and winding core were fabricated on-site. The fabrication error for the position of the coil is demanded to be under 2 mm. Since the can plays a role of a bobbin for the helical coil, the fabrication error of the can must be small. At first, a torus-shaped winding core was prepared with high accuracy of 0.2 mm. Each half pitch of the can was finished by NC machinery in a factory. These were assembled and welded each other on the winding core. The fabrication error of the can was finally performed under 1.5 mm. The accuracy of relative position of the conductor to the can should be kept within 0.5 mm.

From the aspects of stability and reliability as a superconducting coil, the motion of the conductors by electromagnetic force must be small, that is, the rigidity of the coil must be high. The helical coil is considered to be compressed and moved outwards by electromagnetic force. By approximating it to a circular coil with average curvature, the movement of each conductor was calculated by finite element method. It mainly depends on the rigidity of the insulators between conductors. Since fabrication gaps between the conductor and the insulator will be collapsed by the large electromagnetic force, the gap lessen the equivalent rigidity of the coil. The average fabrication gap was submitted to be within 65 μm/layer to keep the stress on the conductor under the yield strength. In order to lessen the fabrication gaps, it is necessary to apply tension on the conductors. Since the helical-coil winding machine is unable to pull the conductors without spoiling the shaped form, we have developed the method to apply tension on the conductors by lateral shift after winding each layer[1]. We can apply almost 50 MPa by shifting by 5 mm. We manage the shaping error of the conductor within 10 %, the maximum relief by slant of each conductor within 0.30 mm, and the average relief by slant within 0.13 mm. In addition, we full up reinforced epoxy resin between the upside of the conductor and the bottom of the layer-to-layer insulator. The resin is cured at room temperature, and the compressive modulus is over 10 GPa which is as half as that of the insulator. The average residual gaps become half of the average relieves by slant.

After trial of winding, on-site winding has started at the beginning of 1995. The conductor for each layer is rewinded on the winding machine from carrying drum. It is supplyed to the shaping head, and it is shaped and fed on the helical-coil-can. It is placed by hand while checking shaping errors. If the value is out of control, the conductor is reshaped by special instruments. After all turns in a layer are in place, they are shifted sideways in the direction that the trajectory of the coil becomes longer. The slant and the position of the conductor are measured. The insulator between layers is put on the conductor with filling the resin. The next conductor is jointed at the end of each layer.

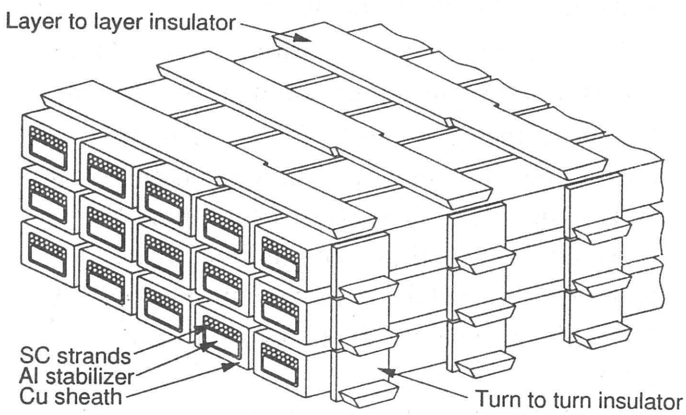

Fig. 1. Schematic diagram of the helical coil.

References
1) T. Senba, et al., proc. of 18th Symposium on Fusion Technology.