Design and Performance Test of an HTS Magnet for 1 MW HTS DC Induction Heater

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Abstract: Compared with a small magnet, the magnet for IMW HTS DC induction heater is larger, and the radius reaches up to 2200mm, which will bring great difficulties to the winding of superconducting magnets. To ensure that the design and fabrication of the large-diameter HTS DC magnet can be a one-shot success, some smaller HTS magnets, including three 200 mm diameter magnets and two 600 mm diameter magnets, have been designed and fabricated. The structure of these magnets is similar to the final 2200 mm diameter prototype magnet, which is wound in a spiral way. Performance test results of all the superconducting magnets have proved that the winding process and curing process of the magnet is feasible and can be used to make large-diameter magnets formally.

1. Introduction
Conventional AC induction heating is widely used in aluminium extrusion plants to preheat the billets to soften the metal before it is pressed in the die of the extruder. Good temperature uniformity of the billet is crucial to avoid cracking or local melting during extrusion which can heavily damage the quality of the aluminium profile product. A typical value of 723.15 K-773.15 K and a temperature deviation of ±2.5% for the billets are required [1]. However, the efficiency of state-of-the-art AC induction heater rated 1MW just reach up to 60% and the 40% energy is moved by the cooling water through the hollow copper coil. In order to improve efficiency, the HTS DC induction heating concept was proposed in [2]. In this concept, the billet is driven by a motor to rotate in a static magnetic field generated by a lossless HTS DC magnet. According to Lenz’s law, the current will be produced within the billet to prevent the rotation of the billet and the mechanical energy of the motor will be converted into the Joule heat heating the billet during the operation. Thanks to the HTS magnet excited by DC no losses are generated, and the efficiency is in line with that of the motor rated 1MW with an efficiency of above 90% [3].

At present, a lot of work has been done on superconducting DC induction heating [4-6], but less research has been done on large induction heaters rated 1 MW or greater. In large HTS DC induction heater, the radius of magnets will be very large, which will bring great challenges to the manufacture of the magnets. The conductor motion raised by Lorentz force is the most important mechanical disturbance source causing the quench or damage of the magnets, such as the separation of the interlayer tapes, the stripping of the curing materials from the tapes and the generation of disturbance energy [7-9]. In the process of winding a magnet, it is necessary to apply a certain tension force to the
tapes to make the superconducting magnet more compact and reduce both the volume of the curing material and the disturbance energy released by the rupture of the curing material.

In this paper, several superconducting magnets with different radius have been designed and fabricated to verify the manufacturing process, and the magnets are manufactured in the order of radius from small to large. Due to the superconducting tapes will be subjected to preset mechanical stresses during winding and the electromagnetic stress during operation, the performance of the magnet subjected to the shock of cold and hot cycles after curing will be evaluated to confirm the feasibility of the manufacturing process. And this will provide a good basis for the formal manufacture of superconducting magnets of 1 MW HTS DC induction heater in the future.

2. Design and Fabrication

2.1. Design ideas

In order to ensure that the final prototype HTS magnets with a diameter of 2000 mm can be made successfully at one time, several smaller HTS magnets, including three with diameters of 200 mm (numbered by 200-1#, 200-2# and 200-3#) and two with diameters of 600 mm (numbered by 600-1# and 600-2#), have been designed and manufactured in the same way as the final prototype magnet wounded in a spiral way. The skeletons of three magnets of different diameters are shown in Fig. 1 and Table 1 shows the specifications of some magnets.

The YBCO tapes are provided by Shanghai Superconductor, which is wrapped with a polyimide insulating layer. The 200-1# magnet is designed to verify feasibility of the manufacture process of the magnet primarily, and 200-2# and 200-3# magnets with the same size as the 200-1# magnet are aimed at verifying the stability of the manufacturing process. In order to confirm that whether the manufacturing process is feasible when the diameter is larger than 200 mm, the 600-1# and 600-2# magnet are designed and manufactured, and the thickness and height of the magnet are equal to about 1/2 of the final prototype magnet. The lead part adopts the G10 epoxy plate as the insulation between the copper lead and the magnet skeleton. Finally, a prototype magnet with a diameter of 2000 mm, which is consistent with the final HTS magnets for 1 MW HTS DC induction heater, is designed and manufactured to verify the manufacture process further. But the thickness of the prototype magnet is only about 1/4 of the final HTS magnets and the length of YBCO tapes used is 1.4 km.

![Figure 1. The skeletons of three magnets of different diameters are shown above.](image)

| Items                        | Values (200-1#) | Values (600-1#) | Values (2000mm) |
|-----------------------------|-----------------|-----------------|-----------------|
| Inner diameter (mm)         | 256             | 600             | 2000            |
| Material                    | Copper          | Red copper      | Aluminium alloy |
| Turns number per layer      | 12              | 12              | 31              |
| Layers number               | 15              | 23              | 7               |
| Turns number                | 180 (12×15)     | 276             | 217             |
| Length of the HTS tapes (m) | 145             | 534             | 1400            |

2.2. Manufacture and test of the magnet

2.2.1 Manufacture of the magnet. During the winding process of the magnets, the appropriate tension applied to tapes can make the tapes subjected to the radial compression stress, which can ensure the
tight bonding of the tapes between the layers and reduce the probability of the stripping of curing materials. However, excessive tension may destabilize the conductor in the inner layer, rupture the curing materials in the excitation process, or even cause the conductor to yield slightly, resulting in the decline of the current-carrying performance of the superconductor tapes. Therefore, an appropriate can reduce mechanical disturbance and improve the stability of the magnets. The 200-1# magnet being wound is shown in Fig. 2 (a). In order to avoid the disturbance of the electromagnetic stress, the magnets will be cured by vacuum paraffin in the curing furnace shown in Fig. 2 (b). The thermal conductivity parameters of paraffin at the temperature of 25K is less than 0.1 W/m·K. And aluminium nitride powder with high thermal conductivity and low conductivity has been chosen as the filling materials to improve the thermal conductivity of curing materials.

Figure 2. Winding of superconducting magnet and curing furnace.

2.2.2 Test of the magnet. In order to simulate the most extreme conditions, the magnets connected with the current lead will be directly put into liquid nitrogen (LN₂), the critical current will be tested after cooling, then removed from the LN₂ and restored to the room temperature. The above operations will be repeated many times to evaluate the performance of the magnet subjected to the shock of cold and hot cycles. Due to the final HTS magnets for 1 MW HTS DC induction heater is cooled by conduction, the 200-1# magnet will also be cooled first by conduction and then the critical current will be tested again in LN₂ to evaluate the effect of conduction-cooled to the magnet. Finally, the critical current of the prototype magnet will be tested under conduction-cooled and in LN₂ respectively to confirm the manufacturing process for the final HTS magnets.

3. Experimental results

3.1. 200 mm diameter HTS magnets

According to the test results, the critical current of the 200-1# magnet immersed in LN₂ before curing is about 65 A. The cold and hot cycle impact experiments were carried out on the 200-1# magnet after curing, and the results are shown in Fig. 3. It can be seen that the critical current has no significant difference, indicating that the 200-1# magnet can be subjected to the shock of cold and hot cycles. Therefore we can confirm that the winding process, curing process and the welding technology are feasible and would not affect the performance of the superconducting tapes, initially meeting the application requirements.

On the basis of the 200-1# magnet, the 200-2# and 200-3# magnets are processed to confirm the stability of the manufacturing process according to the same process as that of the 200-1# magnet. The length of the YBCO tapes for 2# and 3# magnets is 200m and 163m respectively, and the critical current is 58 A and 66 A respectively before curing. The critical current of the 200-2# magnet is slightly lower than 200-3# magnet because the vertical magnetic field generated by the former is stronger than the latter under the same current. And the test results are also shown in Fig.3. It can be seen that the critical current results have no significant difference, indicating that the manufacturing process is stable. And the welding resistance between the YBCO tapes is about 20 nΩ and the resistance between the YBCO tapes and the copper wire is less than 0.5 uΩ in this manufacturing process.

The 200-1# magnet is cooled by conduction after the cold and hot cycle impact experiments, and the cooling curve is shown in Fig. 4. The temperature reaches equilibrium after about 40 hours and the
corresponding cold head temperature is 20 K, while the temperature range of the magnet is 47.5-50 K. In order to detect whether the 200-1# magnet is damaged after conduction-cooled to a lower temperature than 77 K, the critical current was tested again in LN2. And the critical current is 65 A, which is in line with the 200-1# magnet before conduction-cooled and indicates the conduction-cooled has no significant effect on the magnet. The cooling process by conduction is slow and the thermal stress can be released step by step, while the temperature gradient of the direct cold shock of LN2 is huge. Therefore, the effect of conduction-cooled on the cold shock of the magnet is less than LN2 direct immersion cooling. If no damage occurs to the magnet under LN2 direct immersion cooling, the damage of conduction-cooled on the magnet will not be worse.

Figure 3. The critical current test results of the 200-1# magnet have been carried out after curing.

Figure 4. Cooling curve of the 200-1# magnet cooled by conduction.

3.2. 600 mm diameter HTS magnets

The critical current of HTS tapes is anisotropy, and the most important factor that affects the critical current of the tapes at a certain temperature is the magnetic field, especially the vertical magnetic field. Therefore the simulation calculation is aimed at guaranteeing that the vertical magnetic field is nearly equal to that of the final HTS magnet under normal operating conditions.

According to the electromagnetic analysis of 1 MW HTS DC induction heater, in order to ensure the heating efficiency, the air-gap magnetic field should be greater than 0.5 T, and the maximum vertical magnetic field on the magnet surface during steady operation is about 0.35 T. Therefore the 600-1# magnet will be carried out in accordance with the largest vertical magnetic field is slightly greater than 0.35 T.

By loading different currents, it is found that the maximum vertical magnetic field on the tape surface is about 0.4T when the current was 150 A, which was close to the final HTS magnet. The magnetic field profile of the 600-1# magnet without iron core at 150A is shown in Fig. 5. From Fig. 5 (b) we can see that the vertical magnetic field, namely the radial magnetic field at both ends of the magnet, is much higher than in the middle of the magnet. The reason is that the magnetic flux begins to spread into space at the end of the magnet, and a closed path is rapidly formed at the outside of the magnet. Essentially the vertical magnetic field at both ends of the magnet is less affected by the
current at the other part of the magnet, while the magnetic field at the middle part cancels out by the magnetic field generated by the current at the periphery. Since the vertical magnetic field is the most important factor affecting the current carrying capacity of the HTS tapes, the current carrying capacity of the end superconducting turns becomes the decisive factor limiting the overall current carrying level of the magnet.

Figure 5. Magnetic field profile of 600-1# magnet without iron core at 150 A. (a) Total magnetic field (b) Radial magnetic field (c) Axial magnetic field

Figure 6 shows the magnetic field profile with a 400mm diameter iron core at 150 A. The size of the iron core refers to the scale of 1 MW HTS DC induction heater. It can be seen that the magnetic flux is mostly concentrated in the iron core after adding the iron core. And the leakage magnetic field in the air gap might lead to an unbalanced force on the magnet, which further supports the need for paraffin impregnation.

Figure 6. Magnetic field profile of 600-1# magnet with 400mm diameter iron core at 150 A. (a) Total magnetic field (b) Radial magnetic field (c) Axial magnetic field

The critical current of the 600-1# magnet before curing at 77K is 53 A, taking 1 μV/cm as the criterion. And the maximum vertical magnetic field is 0.15 T at 53 A. According to the relationship between the critical current and the vertical magnetic field, the critical current of the YBCO tapes at 77 K is about 50-55 A when the vertical magnetic field is 0.15T. Therefore the test results are in good agreement with the performance of the YBCO tapes. The critical current of the 600-1# magnet after curing at 77K is 55 A, which is basically the same as before curing. Therefore it can be confirmed that the properties of the 600-1# magnet do not degrade after curing.

Figure 7. The critical current test results of the 600-1# magnet have been carried out after curing.
The critical current test results of 600-1# magnet after curing are shown in Fig. 7. It can be seen that the critical current has no significant difference, indicating that the 600-1# magnet can be subjected to the shock of cold and hot cycles and the manufacturing process are feasible for larger diameter magnets. In order to further verify the stability of the manufacturing process, the same process is used to complete the 600-2# magnet and the length of the YBCO tapes used is 66 m longer than 600-1# magnet. The critical current of 600-2# magnet before curing is 42 A, which is lower than 600-1# magnet because of the larger vertical magnetic field generated by the longer tapes. The critical current test results of 600-2# magnet after curing is also shown in figure 7, which is similar to the 600-1# magnet. There is no significant difference in the critical current of 600-2# magnet after cold and hot cycles, which further indicates that the manufacturing process is feasible when the diameter is larger.

3.3. 2000 mm diameter HTS magnet

Similar to the design of the 600-1# magnet, the magnet with diameter of 2000 mm will be carried out and tested in accordance with the largest vertical magnetic field slightly greater than 0.35 T. By loading different currents, it was found that the maximum vertical magnetic field on the tape surface is about 0.35 T when the current is 210 A, which was close to the magnetic field of the final HTS magnet. The magnetic field profile of the magnet without iron core at 210 A is shown in Fig. 8, and it can be seen that the vertical magnetic field at both ends of the magnet is much higher than that in the middle of the magnet.

Figure 8. Magnetic field profile without iron core at 210 A. (a) Total magnetic field (b) Radial magnetic field (c) Axial magnetic field

The 2000mm diameter magnet without iron core is shown in Fig 9(a). The critical current of the magnet before curing at 77 K is 67 A, taking 1.0 μV/cm as the criterion and the maximum vertical magnetic field is 0.11T at 67 A. The critical current of the magnet after curing at 77 K is 69 A, which is basically the same as before curing. Therefore it is also determined that the performance of the magnet does not degrade after curing. The critical current test results of 2000 mm HTS magnet after curing is shown in Fig. 9(b). There is no significant difference in the critical current of the magnet after cold and hot cycles, which indicates that the manufacturing process for a larger radius magnet than 600 mm is feasible.

Since the superconducting magnets of the 1MW HTS DC induction heater are cooled by conduction, the performance of the magnet cooled by conduction is evaluated by experiments. According to the cooling results, the temperature at the proximal end of the superconducting magnet is 25.2K, and the temperature at the distal end is 26.3K, indicating that the overall temperature difference of the superconducting magnet is relatively small, and both are less than the operating temperature requirement of 30k, reaching the expected target temperature.

According to the design value, the maximum design operating current of the system is 150 A, so the system's thermal stability has been evaluated by continuously loading the current at 150 A for 60 min. During the test, the thermal characteristics of different parts including superconducting magnet and current leads showed no significant change, indicating that the system could run reliably for a long time at 150 A. On the basis of the 150 A, the superconducting magnet was loaded with a current of 180 A for continuous operation for 30 min in order to assess the ultimate operation characteristics of the system. As the current value exceeds the design value of the current lead, the lead temperature rises, but the superconducting coil is normal. In order to further explore the ultimate performance of
the superconducting coil, a current of about 275 A was excited. Then the 150A current-carrying characteristics were checked and result indicating that the superconducting magnet was not damaged even if the superconducting strip lost superconducting for a short time.

**Figure 9.** The 2000mm diameter magnet without iron core is manufactured, and its critical current cycle tests are carried out after curing.

4. Conclusion

In this paper, a 200 mm diameter magnet is made first to primarily verify the manufacturing process including winding pre-stressed control and curing process using paraffin wax, which is reproduced by the 600 mm superconducting magnet next, proving that the manufacturing process adopted is feasible and can be further amplified. At the same time, the test results show that the technical parameters of YBCO superconducting tapes are basically consistent with the experimental results, and the technical parameters have a certain basis for the electromagnetic design of the final prototype. The manufacturing process of 200 mm and 600mm diameter superconducting magnets is finally reproduced by the 2000 mm superconducting magnet, which proves that the manufacturing process adopted is feasible and can be further amplified. This provides a good basis for the formal manufacture of superconducting magnets of 1 MW HTS DC induction heater in the future.

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References

[1] M. Fabbri, et al., DC induction heating of aluminum billets using superconducting magnets. COMPEL - The international journal for computation and mathematics in electrical and electronic engineering, 2008, vol. 27, pp. 480-490.
[2] N. Magnusson et al., Induction heating of aluminum billets using HTS DC coils. 2003.
[3] M. Fabbri, et al., Experimental and Numerical Analysis of DC Induction Heating of Aluminum Billets, IEEE Trans. Magn., 2009, vol. 45, pp. 192–200.
[4] A. Stenvall, et al., Electromagnetic viewpoints on a 200kW MgB2 induction heater. Physica C: Superconductivity, 2008, Vol. 468, pp. 487-491.
[5] J. Choi, et al., Practical design and operating characteristic analysis of a 10kW HTS DC induction heating machine. Physica C: Superconductivity and its Applications, 2014, Vol. 504, pp. 120-126.
[6] J. Choi, et al., Characteristic Analysis of a Sample HTS Magnet for Design of a 300 kW HTS DC Induction Furnace. IEEE Transactions on Applied Superconductivity, 2016, vol. 26, pp. 1-5.
[7] C. Lewis, et al., A direct drive wind turbine HTS generator. IEEE Trans. Appl. Supercond., 2007, vol. 21, pp. 1-8.
[8] S. K. Baik, et al., Electrical parameter evaluation of a 1MW HTS motor via analysis and experiments. Cryogenics, 2009, vol.49, pp. 271-276.
[9] P. N. Barnes, et al., Compact, lightweight, superconducting power generators. IEEE Trans. Appl. Magn., 2005, vol. 41, pp. 268-273.