MgB\(_2\) coils for a DC superconducting induction heater

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Abstract. In a DC superconducting induction heater the workpiece to be heated is rotated in a magnetic field generated by superconducting DC coils. Such a heater for preheating of aluminium billets (large cylinders) before their extrusion to profiles is under development in a European project. Two superconducting coils with a diameter in the 1 m range generate a magnetic field of about 0.5 T in the centre of the billet (when the billet is at rest). The coils are wound from MgB\(_2\) superconductor tapes with a critical current of about 400 A at 20 K and 1 T. In this paper we report on the analyses, design and build-up of the coils. Wire design and properties are given for the final choice of wire. Stability analyses show that quench situations can be handled. The design of the two coils is given and their interacting forces computed. Also the winding technique and the coil structure build-up are described. Finally, test results from winding of a small MgB\(_2\) test coil are given.

1. Introduction

Electromagnetic induction ovens are used at aluminium extrusion plants to preheat large aluminium cylinders (billets) before extrusion to profiles. This heating method is one of the large-scale electrotechnical processes with absolutely the poorest energy efficiency. Typically only 55 - 60\% of the supplied power is converted to heat in the billet, the rest is losses in the hollow water-cooled copper conductors of the induction coils.

A novel approach that has the potential to significantly increase the efficiency of aluminium billet induction heating is presently pursued. A static magnetic field is generated by passing DC currents in two superconducting coils. Heat is generated in the billet by letting an electric motor rotate the billet in the magnetic field between the coils and thereby inducing circulating currents and thus resistive dissipation in the billet [1]. The magnetic field is generated without creating losses in the superconductor and hence, the efficiency of the system becomes primarily determined by the efficiency of the motor rotating the billet. With this method, efficiencies approaching 90\% may be reached.

In a European project, a 200 kW rotating billet superconducting induction heater will be designed, built and tested [2]. The superconducting coils will be made of MgB\(_2\) tapes and constitute a crucial part of the heater. In several papers MgB\(_2\) test coils of various sizes are described [3] - [4] and MgB\(_2\) superconductors have also been used for an MRI system with similar size and shape of the coils as the...
coils of an induction heater [5]. In the present work we report on the design, quench analysis, material usage and winding techniques for the coils of the 200 kW induction heater of the European project.

2. MgB$_2$ superconducting tapes

2.1. Tape properties
The primary reasons for using MgB$_2$ superconductors in the coils are the potential low costs for MgB$_2$ wire compared to BSCCO/Ag, YBCO coated conductors or other high-temperature superconductors. Moreover, as the coil is operated in DC, additional conductor length does not yield additional losses and this makes the coil design flexible in terms of conductor expenditure. Compared to low-temperature superconductors the operating temperature of MgB$_2$ at around 20 - 25 K is convenient as cryocoolers can be used in an efficient way and that no liquid helium baths are required.

The MgB$_2$ superconductor used is in the form of 0.65 mm thick and of 3.6 mm wide tapes. The tape has 14 superconducting filaments embedded in a nickel matrix and it has a copper core for thermal stability in case of quenches. Production length of the wire is 1650 m. Figure 1 shows a cross section of an MgB$_2$ conductor.

![Figure 1. Cross sectioned MgB$_2$ superconducting tape.](image1)

2.2. Electrically insulating the tape
An 8 mm wide and 25 $\mu$m thick polyimide film is used to electrically insulate the superconductor. The film can withstand a dielectric stress of several kilovolts and comes in rolls with an adhesive on one side. Figure 2 shows parts of the machine that was built to put the insulation on the superconductor.

![Figure 2. Set-up for folding the polyimide foil around the edges of the MgB$_2$ tape (left) and for firmly pressing it onto the superconductor tape (right).](image2)
The polyimide film is carefully folded around the edges of the MgB$_2$ tape and then the two parts are firmly pressed together. An adjustable speed motor drives the process, and the setup worked flawlessly for speeds up to more than 20 m/min.

3. Induction coils

3.1. Coil parameters and design principles

The 200 kW DC heater prototype utilizes two identical circular coils with the rotating billet placed in-between such that the magnetic field is oriented perpendicular to the billet axis. The inner diameter of the coils is 1.1 m. Each coil has its own cryocooler attached to it, and conduction cooling keeps the operating temperature of the coil in the 20 - 22 K range. The operating current is 200 A which is about 70% of the critical current in the regions of the coil with the strongest magnetic field.

Each coil will be built up by stacking 16 double pancake coils on top of each other and connecting them in series with soldered joints at the outside. Each double pancake has 75 turns inwards and 75 turns outwards of single MgB$_2$ tape. Hence, each double pancake uses around 540 m of MgB$_2$ tape, and the total amount of tape needed for the 2400 turns of each coil is nearly 9 km. The inductance of the coil pair is 18 H, and 360 kJ of energy is inductively stored in the coils when they carry 200 A.

One motivation for using pancake coils and not a solenoid is that it is possible to cool down and test one or a few pancakes during the course of the work to ascertain that the winding and manufacturing process not have severely impaired the properties of the superconducting tapes. Moreover, it will also be possible to replace one of the double pancake coils, even after assembly of the complete stack, in the case of local damages on the superconductor.

The obvious drawback with a stack of pancake coils is that several joints are required. These will inevitably cause some resistive losses, and precautions must be taken both to make certain that all the joint resistances are very low (not exceeding a few micro-ohms) and that the heat generated is efficiently conducted away towards the cold head of the cryocooler. However, also a solenoid coil of this size will require joints as the length of the superconducting tape needed for one coil by far exceeds the current production lengths.

3.2. Forces between the coils

In addition to hoop stress and radial stress, Lorentz forces between the coils have to be taken into account in a two-magnet system. The attractive force component $F_{\text{att}}$ was computed as

$$F_{\text{att}} = \int 2\pi r J r B_r \, da$$

where $J$ and $B_r$ are the average coil current density and the radial magnetic flux density component. The integration was done on the coil cross-section. Figure 3 presents the coil dimensions and the direction of the attractive force. Due to symmetry, it is sufficient to model the problem 2D-axisymmetrically in one quarter of the system cross-section.

![Figure 3. Schematic view of cross-section of coil with dimensions, reduced modeling domain and axis for computing attractive force](image-url)
Figure 4 presents the computed forces as a function of operation current for distances of 600, 700, 800 and 900 mm between the coils. The nominal force at the operating current of 200 A and the coil distance of 800 mm is 33 kN.

3.3. Winding and impregnation

A good thermal conduction throughout the winding is required to have a nearly uniform temperature in the coil and to allow for an efficient conduction cooling. Moreover, as discussed above, high currents and strong magnetic fields give rise to substantial electromagnetic forces, so the mechanical strength and integrity of the windings are also crucial. Hence, the coil should be impregnated with an agent which is a good thermal conductor, adheres well to the polyimide and to metal and which is mechanically strong. Furthermore, its thermal contraction and expansion should be similar to that of metal and it should be electrically insulating (note that a millimeter-wide gap of one side of the superconductor is not covered with polyimide).

Various preliminary winding and impregnation tests were performed and the best results were obtained by using a wet-winding process with an epoxy filled with a high content of alumina (Stycast® 2850). Alumina is electrically insulating but, compared to non-filled epoxy, a good thermal conductor. Figure 5 shows a small part of a sectioned test winding.

The epoxy fills up the space between the tapes and the entire assemble becomes almost solid and strong with very few air bubbles and gaps and thus with a good thermal conduction in all directions. To provide mechanical support, glass fiber bands will be impregnated in the same epoxy and wound around the coil. A copper plate will be glued to the inner diameter of the coil and link this part thermally to the cryocooler head.

Figure 4. Attractive forces between the coils when the billet is at rest.

Figure 5. Detail of cross-sectioned test winding showing parts of eight MgB$_2$ tapes insulated with polyimide and surrounded by epoxy.
4. Quench analysis of the coil system

A 3D quench analysis programme was used to study if the magnets can go through a safe quench. This code is presented in detail in [6]. The coil quench analysis was based on the assumption that a coil quenches at 200 A while the critical current is 300 A. The initial temperature was 20 K in the entire winding. Cases without protection and with 2 Ω and 4 Ω shunt resistors were studied. The quench was expected to be detected when the voltage over the normal zone exceeded 2 V. Results from the quench analysis are presented in Figure 6.

![Figure 6. Hot spot temperature rise (a), current decay (b), normal zone resistance (c), and voltage over normal zone (d). Solid line, dash-dotted and dashed lines are for unprotected system and systems with 2 Ω and 4 Ω shunt resistors, respectively.](image)

Time to quench detection is relatively long, 7 s. This is due to a slow normal zone propagation when compared to windings with lower temperature superconductors. This is typical when operation temperature is lifted up from liquid helium level and can lead to serious quench detection problems in high temperature superconducting windings [7] - [9]. At the time of the quench detection the hot spot temperature has already risen to 78 K. If protection is used the current decay is fast after the detection and the hot spot temperature does not rise substantially any more. Also, the maximum resistive voltage inside the winding stays below 3.5 V. In the unprotected case the hot spot temperature rises to 155 K and the current decay from operation current to 20 A takes 32 s. This long time is due to the high inductance and slow normal zone propagation. Anyhow, this coil appears to be self-protective since the temperature rise to 155 K is not expected to degrade the coil critical current and break up the winding. Still, it is decided to equip the quench detection circuit with a 2 Ω shunt resistor in order to attain faster recovery from a quench situation.

5. Test coil

A smaller double pancake coil was made in order to acquire some experience with the wet-winding procedures and in particular make certain that the tape handling during the winding and cool-down not causes any notable reduction in the current-carrying capability of the superconductor. The test coil has an inner diameter of 200 mm and the two layers each have 39 turns. The left part of figure 7 shows a photo of the test coil before it was placed in the cryostat and cooled down.

The coil was glued on a copper plate which, via a few layers of paper to introduce a thermal resistance, was connected to the cold head of the cryocooler. The coil temperature when cooled down was 32.5 K. To make sure the current leads were colder than the coil, they were glued on a copper plate in direct thermal contact with the cold head. The current was gradually increased while measuring the voltage drop over the coil me. The coil could carry 96 A, whereas at 97 A the voltage increased and the coil quenched. In the right part of figure 7 the result of the coil is compared to the critical current for a single tape measured in 0, 0.2, 0.4 and 1 T applied magnetic fields. For the coil, the maximum magnetic field (appearing at the inside of the coil) at 96 A was about 0.04 T. The measured critical current for the coil is between the lines for 0 T and 0.2 T applied magnetic fields for
the single tape wire. This indicates that the winding and cool-down were performed without causing major damage to the superconductor. Furthermore, no significant reduction in critical current was observed after the quench.

Figure 7. Photo of the test coil (left) and the 96 A critical current at 32.5 K (X) for the test coil compared to single tape critical current as function of temperature for the same MgB$_2$ tape batch (right). The lines are guides to the eye in the region where the critical current-to-temperature dependency is linear.

6. Conclusions
Theoretical and experimental analyses have led to a route for the construction of MgB$_2$ coils for a rotating billet induction heater. A wet-winding technique with electrically pre-insulated tapes is adopted and the coil winding procedure tested on a small coil with satisfactory results. Quench analyses show that the full-scale coils are self-protective, but a 2 Ω shunt resistor will be used for safety and for reduction of cool-down time after a quench. With these results, the next step will be to wind and test a first full-scale double pan-cake coil for the induction heater.

References