Design, Building and Testing of a 10 kW Superconducting Induction Heater

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Abstract—Conventional 50/60 Hz induction heaters for aluminum billets have very large losses. By replacing the copper windings with windings of high-temperature superconducting (HTS) tapes, there is a substantial potential for efficiency improvements, especially if low ac loss HTS tapes become available. To examine the feasibility of using HTS in induction heaters, a first, small-scale working model has been designed and built. The induction coil is made of 24 double pancake coils of Bi-2223/Ag tapes. In the initial test, a workpiece of aluminum situated in the warm bore of the coil was heated up to 300 °C.

Index Terms—Electromagnetic heating, high-temperature superconductors, superconducting coils.

I. INTRODUCTION

ELECTROMAGNETIC induction is widely applied for industrial heating of metals. Alternating currents from a power source is passed through coils to generate a strong time-varying magnetic field. The workpiece to be heated is placed in this field, and the resistive losses due to the electric currents being induced in the metallic workpiece generate heat.

Compared to other industrial heating methods, induction heating is clean, fast and easy controllable. The energy efficiency is in general also good, at least when compared to competing technologies such as gas burners. However, the efficiency of an induction heating process varies strongly with the material properties of the workpiece. When heating magnetic materials such as iron, almost all consumed power is converted to heat in the workpiece. On the other hand, for induction heating of materials that at the same time are non-magnetic and good electrical conductors, e.g. copper and aluminum, the efficiency is only around 50 %, which is very low for an electrical heating process.

Conventional induction heater coils usually have hollow water-cooled copper windings. It has recently been proposed to instead use high-temperature superconducting (HTS) windings to improve the energy efficiency of 50/60 Hz induction heating of copper and aluminum [1]. To pursue and assess the feasibility of this concept, a small-scale working model of an induction heater with HTS windings has been designed and built. To the authors’ knowledge this is the first superconducting induction heater ever built. The present paper reports on this work.

An accompanying paper [2] provides more details on how the energy efficiency can be estimated in such a device. In particular, correct modeling of ac losses in the HTS under different conditions is crucially important.

In order to thoroughly clarify the motivations for building an HTS induction coil, the basic principles behind induction heating of extrusion billets are briefly reviewed initially.

II. INDUCTION HEATING OF EXTRUSION BILLETS

A typical induction heater configuration is shown in Fig. 1. The workpiece is here a billet, i.e. a massive cylinder, placed coaxially inside a solenoid coil.

![Fig. 1. Principles of billet heating.](image)

When passing ac in the coil windings an axial, time-varying magnetic field is generated in the billet. In order to cancel this field, currents are induced in the billet according to Lenz’ law. These currents flow in the tangential direction and primarily in the surface of the billet, see Fig. 1.

Hence, an induction heater is essentially a transformer; where the metallic workpiece to be heated is a single-turn short-circuited secondary winding.

The efficiency $\eta$ of this heating process is...
\[ \eta = \frac{P_w}{P_w + P_c} \]  
\[ \text{where } P_w \text{ and } P_c \text{ are the power dissipated in the workpiece and in the coil windings, respectively.} \]

By setting \( P = R^2 I \) and \( I_w = nI \), where \( R \) is resistance, \( I \) is current and \( n \) the number of turns in the coil, (1) can be reformulated to

\[ \eta = \frac{n^2 R_w}{n^2 R_w + R_c}. \]

The resistances of the workpiece and of the coil winding can be expressed as

\[ R_w = \frac{\rho_w 2\pi (r_w - \delta_w)}{\delta_w}, \quad R_c = \frac{\rho_c 2\pi (r_c + \delta_c)}{\delta_c n} \]

if the coil only has a single-layer winding.

The resistivity of workpiece and coil are \( \rho_w \) and \( \rho_c \), respectively, whereas the inner radius of the coil is \( r_c \) and the workpiece radius is \( r_w \). Both have lengths \( l \).

The skin depth \( \delta \) is determined by the angular frequency \( \omega \) and the relative permeability \( \mu_r \),

\[ \delta = \frac{2\rho}{\sqrt{\mu_r \omega}}. \]

Introducing (3) and (4) into (2) yields

\[ \eta = \frac{1}{1 + \frac{\rho_c \mu_r r_c + \delta_c}{\rho_w \mu_w r_w - \delta_w}}. \]

The windings are normally made of copper, giving \( \mu_r = 1 \). Furthermore, by assuming that the skin depth is small compared to the billet and coil radii, and that \( r_c \approx r_w \), i.e. the coil closely surrounds the workpiece, (5) can be simplified to [3]

\[ \eta = \frac{1}{1 + \frac{\rho_c}{\rho_w \mu_w}}. \]

This equation shows that with a workpiece of high resistivity and permeability, such as steel, the efficiency approaches 100%. In contrast, when heating a non-magnetic workpiece with a resistivity comparable to the resistivity of the copper in the coil windings, the root term approaches unity and the efficiency is only around 50%. Hence, in the latter case approximately equal parts of the consumed power are dissipated in the coil windings and in the billet.

In aluminum extrusion plants 50/60 Hz induction heaters of the configuration shown in Fig. 1 are used to preheat billets from room temperature to around 500 °C to soften the metal before the billet is pressed through the extruder. A high throughput is required, so these heaters are very compact and powerful. The largest heaters operate at magnetic fields up to around 0.7 T and with power ratings exceeding 1 MW. Multi-layer coils are in many cases used, so the efficiency is somewhat higher than given by the single-layer efficiency expression (6). However, the fundamental problem of obtaining a strong magnetic field without too high resistive losses in the windings remains, and large state-of-the-art industrial induction heaters for aluminum and copper have at best an efficiency of only around 60%. Thus, almost half the consumed power is dissipated in the copper windings and converted to “useless” cooling water at around 30 – 40 °C.

The efficiency of the heating process can be improved by reducing the ratio \( \rho_c/\rho_w \) in (6). The parameter \( \rho_c \) is determined by the properties of the workpiece, so the remaining option is to lower \( \rho_w \). Using HTS in the coil windings emerges as an interesting approach, especially viewed in the light of the construction of a 500 kVA HTS power transformer operating with an overall efficiency of 99.3% (cooling penalty factor included) [4]. Loss reduction is considered a major driving force for developing HTS transformers, but as indicated above, the potential for efficiency improvements is far greater in some induction heaters.

III. HTS INDUCTION HEATER CONSTRUCTION

A. Superconducting Coil

The induction coil was made using stainless steel reinforced multi-filamentary Bi-2223/Ag HTS tape acquired from American Superconductor Corp. The tape was delivered with a 50 µm thick kapton wrap-on foil that provides electrical insulation up to 2 kV. The tape dimensions, including the stainless steel reinforcement and the electrical insulation was 4.2 mm × 0.4 mm, and the self-field critical current \( I_c \) at 77 K was greater than 115 A.

Double pancake coils were wound using two tapes in parallel. Fiberglass fabric was wound around the outer periphery of the double pancakes to a thickness of approximately 3 mm. The coil including this fiberglass layer was then vacuum impregnated with epoxy containing 50 weight percent fine quartz powder. The quartz largely eliminates problems due to differences in thermal expansion properties between the metallic conductor and epoxy. The fiberglass reinforced epoxy at the outer perimeter provides sufficient mechanical strength against electromagnetic forces directed outwards, whereas the almost completely bare inner surface gives good thermal contact between the HTS and the coolant.

An 80 µm diameter varnish-insulated copper wire was wound bifilarly between the parallel HTS tapes in each double pancake coil. By passing a low dc current and measuring resistance changes in this wire, a good estimate of the average temperature increase in the pancake is obtained. Around 77 K the resistivity of copper changes with more than 3%/K.
The induction coil was assembled by stacking 24 double pancake coils on top of each other with a 1 mm gap to improve cooling. Two and two double pancake coils were connected in parallel, yielding totally four HTS tapes in parallel. The pancakes were joined by removing the kapton film and soldering the tapes to a small copper sheet by using a solder with melting point at 120 °C.

Fig. 2 shows a photo of the assembled coil. The height is 257 mm, the inner diameter 130 mm, and the total number of (single tape) turns is 1034.

B. Induction Heater Assembly

Fig. 3 shows a cross-section of the complete induction heater, including cryostat, billet and thermal insulation.

The two uppermost and the two lowermost double pancakes have fewer turns and somewhat greater inner diameters than the rest. This feature together with the magnetic flux diverters, significantly reduce the radial magnetic field at the coil ends.

Without these precautions the ac losses would have become unacceptably high in this region and the \( I_c \) of the coil much lower. The flux diverters are located both inside and outside the cryostat and are made of stacked 0.5 mm transformer sheets embedded in epoxy.

The entire cryostat is made of fiberglass reinforced epoxy. The 3 mm gaps between the two innermost and between the two outermost tubes, as well as the double bottom are filled with 12 sheets of non-inductive “superinsulation” and evacuated to \( 10^{-3} \) Torr. The cryostat is 500 mm high, has an outer diameter of 300 mm and is filled with liquid nitrogen.

The 3 mm gap between the inside of the coil and the cryostat wall allows for efficient heat transfer from this high-field and high-loss region of the coil to the nitrogen bath, and does also give an efficient vertical flow of coolant.

A 10 mm refractory insulation liner is placed at the inside of the 106 mm diameter warm bore. The insulation can withstand temperatures up to 850 °C, has a density of 0.3 kg/m³, a thermal conductivity of 0.024 W/m·K, and a heat capacity of 1050 J/kg·K. It is kept in position by a 0.5 mm stainless steel sheet that is split lengthways to prevent circulating currents.

The workpiece to be heated is a solid cylinder of aluminum, 215 mm high and 80 mm in diameter, placed in the center of the bore. Hence, the distance between the warm billet and the liquid nitrogen is only 22 mm.

C. Rating Estimates

With two and two double pancake coils connected in parallel the inductance of the coil is 4.1 mH, giving a 50 Hz reactance of 1.3 Ω. The induction heater is a largely inductive device with a reactance-to-resistance ratio of around 10.

A strong magnetic field reduces \( I_c \) of the HTS significantly. Furthermore, ac losses may result in a higher temperature in the HTS than in the liquid nitrogen, lowering \( I_c \) even further. Assuming the current distributes equally among the four parallel tapes, the optimum total current is estimated to 190 A_{rms}. Increasing the current further will eventually cause local thermal run-away in the most heavily stressed parts of the HTS. The windings are designed for an operating temperature of about 80 K at 190 A_{rms}.

Finite element analyses [2] show that the maximum magnetic field at 190 A_{rms} is 250 mT_{rms}, and that the flux diverters limit the maximum of the radial component to around 40 mT_{rms}. Furthermore, these analyses also indicate that at 190 A_{rms} an average of 5100 W will go to heating of the
billet, whereas the losses in the HTS coil become around 250 W. When taking a cooling penalty factor of 12 into account, the overall energy efficiency is estimated to 59 %, and the power rating of the device approaches 10 kW. Cryostat heat leaks, losses in the iron and through the current leads contribute around 10 % to the total losses. The billet will heat up from room temperature to 500 °C in approximately 4 min.

IV. INITIAL TESTING

A. DC Tests of the HTS Coil

In order to verify that the HTS tape not had suffered any damage during winding and assembling the coil, and that the flux diverters worked as intended, dc tests were carried out. Fig. 4 shows dc voltage drops as a function of current across each two parallel double pancakes on the upper half of the coil, both with and without flux diverters.

![Fig. 4. Current – voltage relationships across two and two parallel double pancake coils when passing dc, both without (open symbols) and with (solid symbols) flux diverters mounted.](chart)

Without the flux diverters $I_c$ was lowest in the pancakes at the ends of the coil. With flux diverters in place the overall current carrying capability of the coil increased significantly, from around 220 to around 340 A, now limited by $I_c$ in the pancakes in the mid section of the coil. Similar results were obtained on the lower half of the coil.

B. Initial Heating Tests

50 Hz testing of the complete HTS induction heater has just begun, and only a few preliminary results have been obtained.

Fig. 5 shows the temperature development 4 cm into the billet and between the inner wall of the cryostat and the thermal insulation during a test run where 108 A$_{rms}$ was applied for 8.5 min. The power source supplied around 2 kW.

After the power was switched off, the upper inner flux diverter and the thermal insulation on top of the billet were removed, and the billet was pulled out to cool down.

![Fig. 5. Temperatures obtained with thermocouples during a heating.](chart)

By considering the power consumption, the temperature increase in the billet and the liquid nitrogen boil-off, the overall efficiency of the heating is calculated to 35 %.

The heater is designed for 190 A$_{rms}$ and a significantly better efficiency, but attempts to increase the current beyond 110 - 120 A$_{rms}$ were not successful. Voltage drop and temperature recordings clearly revealed excessive heating in some of the pancake coils, indicating that the flux-flow losses at some locations became unacceptably high.

Subsequent examinations indicate that these difficulties probably are due to uneven current sharing between double pancake coils that are connected in parallel. Connecting all double pancakes in series will most likely solve these problems. Further testing (at half the currents and twice the voltages compared to the original plans) will be performed after the coil has been modified this way.

V. DISCUSSION AND CONCLUSIONS

No fundamental technical obstacles were encountered during design, building and initial testing of a small-scale HTS induction heater. However, the tests revealed problems with uneven current sharing in parallel pancake coils, and modifications are required to reach the targeted power and efficiency ratings.

In the present work standard dc HTS tapes are used. If low ac loss tapes become available, it seems possible to build an HTS based induction heater that is significantly more efficient then the 50/60 Hz aluminum billet heaters industry uses today.

REFERENCES


