Induction heating of aluminium billets using superconducting coils

Abstract

It is proposed to apply high-temperature superconducting (HTS) tape in the coil windings for induction heaters for aluminium or copper extrusion billets. The potential for efficiency improvements is substantial, as conventional copper coil induction heaters rated for up to around 1 MW operate with an overall efficiency of typically only 50–60%. The efficiency of a HTS induction heater depends very much on the performance of the HTS tape, in particular the magnitude of the AC losses. A small-scale induction heater demonstrator based on HTS tape is being designed.

Keywords: Induction heating; Coil; AC losses

1. Introduction

For superconducting materials to attain a wide application as conductors in electric power components clear benefits compared to using conventional copper or aluminium conductors must be achieved. The very large difference in physical properties between for example aluminium conductors and BSCCO/Ag high-temperature superconducting (HTS) tapes is a great advantage in this context, as this may cause novel and innovative component designs to become technically and economically feasible. For example, the order of magnitude greater operating current density in BSCCO/Ag tapes can lead to lighter, more compact transformers. In a number of applications, e.g. on oil rigs, reduced transformer weight has a significant economical value.

However, the cost of the superconductor itself, and the cost of keeping it at cryogenic temperatures quite often make it difficult to compete with conventional technology. The majority of conventional power components are by most standards very reliable, rather inexpensive and highly efficient. Thus cases where the use of superconductors clearly will improve cost/efficiency are few and far between, at least when assuming a superconductor cost and performances that are likely to be available in a foreseeable future.

The present paper proposes a novel application of nitrogen-cooled superconductors where the potential for energy savings is substantial and obvious. By using BSCCO/Ag windings instead of copper windings in coils for 50/60 Hz induction heating of aluminium or copper extrusion billets the efficiency of the heating process can be significantly improved.

2. Induction heating of aluminium and copper billets

Induction heating is widely applied for heating of metals because it is a clean, fast and in most cases a very energy-efficient method. An alternating current is passed through the copper windings of a coil to generate a time-varying magnetic field. The field induces currents and thereby resistive losses in the workpiece to be heated, (see Fig. 1).

For a single-layer coil the efficiency η of this process, i.e. the ratio between the power dissipated in the workpiece and the overall power consumption is to the first approximation expressed by

$$\eta = \frac{1}{1 + \sqrt{\frac{\rho_c}{\rho_w \mu_w}}} \tag{1}$$

where ρ_c is the resistivity of the coil conductor material, ρ_w is the resistivity of the workpiece and μ_w is the relative magnetic permeability of the workpiece [1].

This equation shows that with a workpiece of high resistivity and permeability, such as steel, the efficiency approaches 100%.

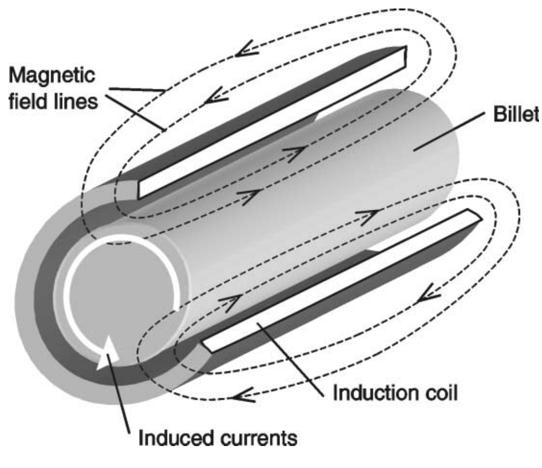

Fig. 1. Principles of induction heating of a massive cylinder (a billet).

On the other hand, 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%. By using multi-layer coils the efficiency can be somewhat improved, but it is still extremely poor compared to almost all other electrical heating processes. For example, 50/60 Hz industrial induction heaters for preheating aluminium extrusion billets (massive cylinders) have power ratings up to around 1.000 kW and operate at an efficiency of typically 55–60%. Thus, nearly half the consumed electric power is dissipated in the hollow, water-cooled copper windings of the induction coils, and then converted into 'useless' cooling water at temperatures around 30–40 °C.

The only way to increase the efficiency of this process is to reduce the ratio ρ_c/ρ_w in (1). The parameter ρ_w is determined by the properties of the workpiece metal, so the remaining option is to lower ρ_c. An interesting approach is to reduce ρ_c by replacing the copper windings of the coil with BSCCO/Ag superconducting windings.

3. Design of small-scale demonstrator

A small-scale induction heater demonstrator, based on BSCCO/Ag tape, for heating of aluminium billets is in the design stage. The heating power will be of the order 5 kW and the billet (length 20 cm, diameter 8 cm) should be heated from room temperature to 500 °C. The HTS coil will operate at 77 K and be exposed to a maximum field of about 400 mT (peak) parallel with the face of the tape.

The efficiency of the induction heater is determined by the AC losses in the HTS coil and by thermal leakage into the cryostat and also from the billet to the surroundings. The important issue is the AC losses. These losses are determined by the performance of the HTS tape, the design of the coil and the efficiency of the cooling machine. The relevant figure of merit for a conductor is the AC losses per unit carried current and unit length (W/A m). In Fig. 2 the efficiency of the induction heater is given as a function of the average AC

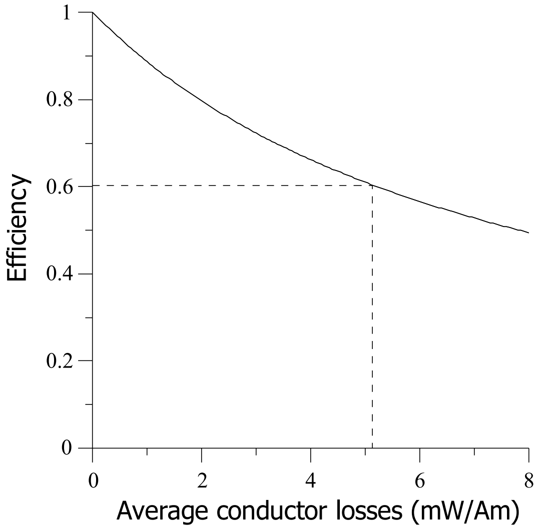

Fig. 2. Calculated efficiency of a 5 kW induction heater as a function of average AC losses in the HTS coil operating at 77 K. A cooling penalty factor of 20 has been assumed and the thermal losses have been neglected. The dashed line corresponds to what can be expected from DC HTS tapes available today.

losses in the HTS coil. The cooling penalty factor at 77 K is assumed to be 20.

A proper design of the HTS coil is of importance to keep the losses low. Every conductor has an optimal operating current at a given field and temperature [2]. This current is always close to the in-field critical current as determined by the 1 μV/cm criterion. In parts of the coil where the losses are high, the current can be greater than the critical current allowing flux-flow losses to appear. At the coil ends the magnetic field contains substantial components perpendicular to the face of the tape. The perpendicular field results in large losses and need to be reduced. One method of achieving this is to insert flux diverters consisting of magnetic materials at the coil ends to straighten up the field [3,4].

The efficiency of the induction heater depends very much on the performance of the HTS tape. With the non-twisted DC tapes available today we expect average losses of the order 5 mW/Am corresponding to an efficiency of 60% for the small-scale demonstrator, see Fig. 2. The development of an AC HTS tape can improve this efficiency significantly. A reduction of the AC losses in such a tape to one third of the AC losses in the DC tapes increases the efficiency of the induction heater with over 20 percentage points. This efficiency increase makes the potential for energy savings more obvious in the induction heater than in e.g. a transformer where the same loss reduction increases the efficiency with only fractions of a percentage point.

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