Recent development and research activities of induction heater with high- T_c superconducting magnets for commercialization

Jongho Choi¹ · Chan-Kyeong Lee¹ · Sangho Cho¹ · Minwon Park² · In-Keun Yu² · Masataka Iwakuma³

© Springer Nature Switzerland AG 2018

Abstract

Supercoil Co., Ltd. had commercialized a 300 kW-class superconducting induction heater (SIH) that is induction heater energized with high temperature superconducting (HTS) magnets on the end of 2017. Supercoil mainly produces many kinds of superconducting magnets and their application devices. Supercoil has a technology to keep thermal stability and reliability in the operation of a superconducting magnet against uneven quench through the metal insulation winding method. The performance test results of the HTS magnet as well as the 300 kW SIH were presented in the paper. Several components on the 300 kW SIH were introduced. Two HTS magnets were installed on the two iron cores and the excitation test results including terminal voltages, magnetic flux density and temperatures of the cryogenic cooling system were presented. The heating test results were shown with several pictures and graphs, and then they were analyzed for the energy efficiency. These results were useful for the commercialization of SIH to heat various metals such as stainless steel, copper and titanium alloys etc.

Keywords Induction heating · HTS magnet · Stainless steel · Aluminium heating · Extrusion and forging

1 Introduction

The superconducting induction heater (SIH) is a preheating machine for the products manufactured from the extrusion and forging processes. An SIH is applicable to heat all the current conducting materials including non-ferrous metals and ferrous metals, such as aluminum, copper and brass, magnesium, titanium alloys, stainless steel and ferrous carbon steel [1–7].

The target temperature of metal billets varies according to the kinds of metals. The temperature distribution of the metal billets is characterized by the electrical conductivity, thermal conductivity, permeability of the heating material and frequency of the induced current [8]. A magnetic field is generated by the superconducting magnet. The optimized magnetic field pattern is determined through the finite elements method (FEM) simulation in order to meet the temperature condition for the customer products. An

SIH is available to get best product quality after the extrusion and forging process.

In this paper, the excitation test of the HTS magnet with iron cores and performance test of the SIH were performed and the results were presented. The components of the 300 kW SIH were introduced and the operation characteristics including terminal voltages, magnetic flux density of the magnets and temperatures of the cryogenic cooling system were analyzed. The heating operation for the aluminum billet was tested and the several pictures taken by thermo-graphic camera were shown to prove heating process. The machine energy efficiency was analyzed through accumulated electrical energy and the surface and core temperatures of the aluminum in operation. These test processes are useful for heating characteristics analysis of the various metals such as stainless steel, copper and titanium alloys for commercialization.

✉ Jongho Choi, jongho.choi36@gmail.com | ¹Supercoil, Changwon 51140, Republic of Korea. ²Changwon National University, Changwon 51140, Republic of Korea. ³Kyushu University, Fukuoka, Japan.

Table 1 The specifications of a 300 kW superconducting induction heater

Parameter	Value
Heating power	Max. 300 kW
Available metal billet size (D: diameter, L: length)	Max. D230 mm × L700 mm
Rotating speed range	300–600 rpm (constant torque mode)
Starting method	Inverter starting (V/F control)
Maximum heating temperature	Max. 1100 °C
Heating time	Depends on the billet type
Efficiency	Max. 90%
Magnetic field generation method	By superconducting magnet; HTS magnets with iron cores
Total length of HTS tape used	3.4 km
Charging and discharging time	Min. 44 min up to 440 A with 0.1 A/s ramping rate
Magnetic field strength at the center between two HTS magnets	Max. 1.3 T at 440 A with iron cores

2 System components of superconducting induction heater

The 300 kW SIH was configured with three systems, a magnetic field generation system, rotating system, and loading and unloading system. A magnetic field generation system includes the HTS magnets, operating equipment, excitation and measurement devices. The rotating system has an induction motor, spindle unit to grip a metal billet and electrical devices for rotation. The loading and unloading system is important issue for total productivity improvement in coincidence with the process flow of customer's manufacturing line. Also, the detailed specifications of the SIH were described in this section.

2.1 Major specifications of the SIH

In the detailed specification, the maximum heating power is to be 300 kW. The rotating speed range is from 300 to 600 rpm with inverter control. The heater efficiency is at maximum 90%. The minimum time to excite the magnets is 44 min up to 440 A with 0.1 A/s ramping rate.

A 300 kW SIH is available to heat maximum temperature of 1100 °C of the metal billet, but the heating time is dependent on the metal types. They have different material characteristics such as heat capacity, density, and relative resistivity. In the case of aluminium billet, it takes 180 s to heat 540 °C, whereas it takes 360 s for a stainless steel billet to heat up to 850 °C (Table 1).

2.2 System components

The first component is a magnetic field generation system. As a core unit of SIH, it generates the uniform magnetic field through the metal billet. The HTS magnets

Fig. 1 Two HTS magnets with two iron cores to generate magnetic fields

with iron cores are located in parallel as shown in Fig. 1. The operation of the magnets is very reliable, because they adapted the metal insulation method and the cooling temperature of the magnet was kept stable during the excitation process.

As indicated in Fig. 2, the second important component is rotating system to heat metal billet as heat energy source. Two hydraulic spindle units hold the metal billet and keep it rotate possible with holding pads. Holding pads retain appropriated friction with the force as strong as the rotating torque during the rotation. In addition, it measures the length of the metal billet prior to the heating process and check whether the product is well gripped. The induction motor rotates the metal billet mechanically and the induced current is generated inside the billet, electrically. The heating energy is transferred to the metal billet.

The third component is loading and unloading system. The loading and unloading system functions to locate the metal billet at the specific position for rotation after loading, and then the billet is unloaded through a conveyor

Fig. 2 Hydraulic spindle unit to grip the metal billet and induction motor for rotation coupled with it

unit after heating was completed as shown in Fig. 3. These loading and unloading units are changeable to customer requirement conditions.

3 Excitation test results of HTS magnets with two iron cores

Two HTS magnets were assembled with two cryostats with two dual stage Gifford McMahon (GM) cryo-coolers. Two HTS magnets are connected through cryogenic current lead on the 2nd cooling stage [9]. In the conduction cooling system operation, the total cooling time took 2 days and 14 h. The temperature at the 1st stage of the cryo-cooler was saturated at 42.3 K. Two HTS magnets' temperatures on the 2nd stage were cooled down and saturated at below 6 K.

First, the HTS magnet excitation test was performed without iron cores. One of two HTS magnets, HTS magnet A, was estimated to have an inductance of 528 mH without an iron core. A characteristic resistance of the non-insulated HTS magnets is a parallel resistance to the

Fig. 3 Loading and unloading units

magnet, and is calculated by the rate of the inductance divided by the time constant [10, 11]. The characteristic resistance was calculated to 23.6 m Ω . Therefore the time constant to the charge magnetic field was calculated to 22.4 s. As shown in Fig. 4, the maximum magnetic field at the center of the HTS magnet A is 1.02 T at 540 A of the input current. And the maximum magnetic flux density at the center between two HTS magnets is 0.69 T at the same current.

Second, the excitation test was performed with iron cores installed on the SIH. When the current was supplied into the magnets with a 0.3 A/s ramping rate up to 440 A, the magnetic field increased as the magnetization characteristics of the iron yokes. The magnetic flux density at the center between two HTS magnets was measured as 0.75 T at the input current of 140 A. And the maximum magnetic flux density was measured as 1.3 T. All the magnet temperatures are stable during the operation. The terminal voltages increased with inductive voltage and the magnetic field at the center between the two HTS magnets was saturated every ramps as shown in Fig. 5.

4 Operation results and their analysis of the 300 kW SIH operation for aluminium billet

The 300 kW SIH, called as a preheating furnace, heats a round metal billet for forging and extruding products. In this operation test, the aluminium billet (AL6061) was used. The billet length is 700 mm and the diameter is 228.6 mm; 9 inch, and the weight is 77.6 kg. To calculate the machine efficiency, the final temperature of the aluminium billet and the total input electrical energy from the source should be measured. Two thermocouples were installed at the center hole of the aluminium billet and

Fig. 4 The current and magnetic field curves of HTS magnets without iron cores according to the time

Fig. 5 The terminal voltages curves of HTS magnets with iron cores according to the input current

at the loading jig for measuring the surface temperature of the aluminium billet, respectively. The aluminium billet was heated up for 180 s after the motor starting. It takes

25 s for the induction motor to reach the rated speed of 592 rpm. After 180 s including motor starting time, the motor was terminated within 20 s. The pictures of the aluminium billet taken by thermo-graphic camera during heating process were shown in Fig. 6. The aluminium billet was heated up to 558 °C of the average temperature between surface and center temperature. The maximum temperature at the surface of the billet was measured to 564 °C after the billet was completely stopped. The maximum temperature at the center hole of the billet was measured to be 552 °C through the real time measurement, as shown in the Fig. 7. Heating energy in the aluminium billet was calculated to be 54,240 kJ by considering the average temperature, heat capacity and weight.

The total input electrical energy including all components such as electrical devices, measurement units, inverter, cryogenic and hydraulic system etc. was measured to be 16.8 kWh for heating time. Namely, the total input energy was estimated to be 60,480 kJ. The total efficiency

Fig. 6 Pictures of the aluminium billet taken by thermo-graphic camera during heating process

Fig. 7 There are two temperature curves. And the total input energy from the power source and the aluminium billet energy calculated with the center temperature of the billet were presented

Fig. 8 The stainless steel billet heating test was also performed and the test picture was presented

of the heater was calculated to 89.7%. This result was very successful.

After the aluminium billet heating test, the heating test for stainless steel billet was also performed. The stainless steel billet was heat up to 850 °C as shown in Fig. 8. The maximum heating power of the SIH was 300 kW and the total heating time was needed 360 s.

5 Conclusion

The excitation test of the HTS magnet and performance test of the SIH were performed and the results were analyzed. The components on the 300 kW SIH were described in detail. The operation characteristics including terminal voltages, magnetic flux density of the magnets and temperatures of the cryogenic cooling system were analyzed. The heating operation for the aluminum billet was tested for 180 s to reach the 564 °C of the billet temperature. The pictures taken by thermo-graphic camera were proved the heating performance. The machine energy efficiency was evaluated to be almost 90% through accumulated electrical energy and the final average temperatures of the aluminum billet. These test process will be helpful for heating characteristics analysis of the various metals such

as stainless steel, copper and titanium alloys for commercialization of the SIH system.

Acknowledgements This work was supported by the Technological Innovation R&D Program (S2469253) funded by the Small and Medium Business Administration (SMBA, Korea).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Davies EJ, Simpson PG (1979) Induction heating for industry. *Electron Power* 25(7):508–515
2. Zinn S, Semiatin SL (2011) Elements of induction heating design, control, and applications. ASM International, Materials Park
3. Runde M, Magnusson N (2003) Design, building and testing of a 10 kW superconducting induction heater. *IEEE Trans Appl Supercond* 13(2):1612–1615
4. Magnusson N, Bersås R, Runde M (2004) Induction heating of aluminum billets using HTS DC coils. In: *Proceedings of the institute of physics, conference series*, vol 181, pp 1104–1109
5. Fabbri M, Morandi A (2008) DC induction heating of aluminum billets using superconducting magnets. *COMPEL Int J Comput Math Electr Electron Eng* 27(2):480–490
6. Choi J et al (2014) Practical design and operating characteristic analysis of a 10 kW HTS DC induction heating machine. *Physica C* 504:120–126
7. Choi J et al (2015) Fabrication and testing of a prototype 10-kW class HTS DC induction heating machine. *J Supercond Novel Magn* 28(2):657–661
8. Choi J et al (2015) Design and performance evaluation of a multi-purpose HTS dc induction heating machine for industrial applications. *IEEE Trans Appl Supercond* 25(3):1–5
9. Choi J et al (2018) An effective cryostat design of conduction-cooled HTS magnets for a 300-kW-class superconducting induction heater. *IEEE Trans Appl Supercond* 28(3):1–5
10. Choi J et al (2016) Characteristic analysis of a sample HTS magnet for design of a 300 kW HTS DC induction furnace. *IEEE Trans Appl Supercond* 26(3):1–5
11. Wang X (2013) Turn-to-turn contact characteristics for an equivalent circuit model of no-insulation ReBCO pancake coil. *Supercond Sci Technol* 26(3):035012