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Development status of DC induction heating device for aluminum billets using high temperature superconducting magnet

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***Abstract*—The induction heating by rotating the aluminum billet in a strong DC magnetic field (DC induction heating) has been demonstrated to show high efficiency [1]. By applying HTS magnets for the DC induction heating, it is possible to significantly improve the heating capacity and the energy efficiency compared to the conventional high frequency induction heating. Research and development of DC induction heating using high temperature superconducting (HTS) magnets has been actively conducted in Europe since the early 2000s and a commercial model was developed around 2008. Subsequently, R&D was also started in Korea and China.**

In 2008, Zenergy Power in collaboration with Bültman GmBH has developed a commercial DC induction heating device using HTS magnets [2]. The HTS magnet of this device made of BSCCO tape with 700 mm × 400 mm room temperature bore is placed on the center leg of E-shaped iron core with two separated air gaps. The two aluminum billets can be processed in parallel. The billet size range is 152 - 177 mm in diameter and 690 mm in length. The output power is 360 kW at the rotational speed of 240 - 750 rpm. This devoce was installed in Weseralu's aluminum plant in 2008 and 350,000 billets (about 10,000 tons, 2.2 ton/hr) were heat-treated in the three years from 2008 to 2010.

The Chinese research group (Shanghai Jio Tong University and others) has developed a 1 MW-class heating device for billets of 460 - 640 mm in diameter [3]. The HTS coil wound with SST (Shanghai Superconductor) REBCO tape wire coupled with the iron core. The iron core has two air gaps as same as that of Zenergy's device. The magnetic field applied to the billets in two air gaps is about 0.45 T. The total wire length exceeds 18 km and the inductance in combination with the iron core is 189 H. In this device, two motors with different outputs are used. In the rapid heating from room temperature, the main motor is used to input large power. After rapid heating, it is switched to the auxiliary motor with the smaller output and the heat input is controlled to equalize the temperature distribution. The proper use of the large and small motor contributes to improve overall efficiency. The overall dimensions of the machine are 14 m/6.5 m/2.5 m and the weight of the iron core is 130 tons.

Supercoil Co. Ltd. and Changwon National University have developed a 300 kW-class DC induction heating system using high-temperature superconducting coils for aluminum billets

[4]. In this device, two HTS coils wound by the SuNAM REBCO tape wire are used. Each HTS coil is separately enclosed in the cryostat with the room temperature bore. These two HTS coils are placed against each other combined with a C-shape iron core. The iron core through the HTS coil is partly movable in the gap direction corresponding to the billet diameter. The operating temperature and rated current of the HTS coils are 10 K 650 A respectively. The inductance is 1.6 H when combined with the iron core and the magnetic field at the center of the air gap is up to 1.5 T. The processable billet size is within 240 mm in diameter and 700 mm in length.
In Japan, a demonstration device of DC induction heating of aluminum billets using HTS magnet has been developed by the group of Terral Inc., Niigata University, Chubu Electric Power Company and AIST [5]. The heating capacity of this demonstration device is 400 kW to heat 40 aluminum billets of nominal diameter 6 inches (about 155 mm) and length 500 mm from 20°C to 500°C per hour. The HTS magnet consists of a pair of racetrack coils wound by REBCO tape of Super-OX (now Faraday Factory Japan). The HTS coil is wound directly around the iron core. This part is located in the cryostat and cooled to cryogenic temperature. The backs of the two sets of HTS coils are connected by a yoke placed at room temperature. This structure can effectively save the necessary amount of HTS tapes in the coils. At the operating temperature of 20 K, the HTS magnet can apply the magnetic field of 1 T to the aluminum billet at the rated current of 200 A. The heating power of 400 kW can be input to the billet at 750 rpm. It was demonstrated that the aluminum billet with the nominal diameter of 6 inches and a length of 500 mm can be heated from room temperature to 500°C within 60 seconds and the heating efficiency was 74.5%. It was also demonstrated that through the continuous heating operation of 90 billets/2 hours, the soundness of the HTS magnets was not compromised.
Table 1 summarizes the specifications of these developed DC induction heating device using HTS magnet.

***Keywords (Index Terms)*— DC induction heating, billet heater, superconducting magnets**

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Table 1. Comparison of specifications developed DC induction heating device using HTS magnet.

	Zenergy power, Bültman	Shanghai Jio Tong Univ., etc.	Supercoil, Changwon Natl. Univ.	TERAL, Niigata Univ., etc.
Output	360 kW	1.1 MW	300 kW	400 kW
Billet size	5 – 7 inch × 690 mm	Φ 446 × 1500 mm	Φ 230 × 700 mm	6 inch × 500 mm
HTS coil	BSCCO (Sumitomo) *W* 4.2 mm × *t* 2.7 mm Racetrack, Pancake --- I_c : 125 A @ 40 K, 1 T I_{op} : 100 A @ 22 – 24 K Tape length : --- GM Refregerator × 2	REBCO (Shanghai ST) *W* 4.8 mm × *t* 0.43 mm Circular, Pancake 936 turns/coil × 3 coils I_c : 170 A @ 30 K (coil) I_{op} : 130 A @ 25 K Tape length : 18024 m GM cryo-cooler × 2	REBCO (SuNAM) *W* 12.1 mm × *t* 0.1 mm Racetrack, Pancake 300 turns/coil × 2 coils I_c : --- I_{op} : 440 A @ 10 K Tape length : 3407 m GM cryo-cooler × 2	REBCO (SuperOX) *W* 12 mm × *t* 0.11 mm Racetrack, Pancake 700 turns/coil × 2 coils I_c : 600 A @ 40 K, 2.5 T I_{op} : 200 A @ 20 K Tape length : 2300 m GM cryo-cooler × 2
Center magnetic field	---	0.46 T (@ 130 A)	1.3 T (@ 440 A)	1.06 T (@ 200 A)
Drive motor	2 motors 240 – 750 rpm	Main : 560 kW × 2 motors Sub : 185 kW × 2 motors 240 – 720 rpm	300 kW × 1 motor 300 – 600 rpm	400 kW × 1 motor 250 – 750 rpm
Heating time	140 s (Φ 155 × 690 mm)	12 min (Φ 446 × 1500 mm)	200 s (Φ 230 × 700 mm)	60 s (5 inch × 500 mm)
Efficiency	80 %	80.6 %	89.7 %	74.5 %
Size Weight	--- ---	L 14 m × H 2.5 m × W 6.5 m > 130 t (iron cores)	L 7.4 m × H 2.9 m × W 4.7 m 45 t	L 5.5 m × H 3.2 m × W 1.8 m 10 t

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