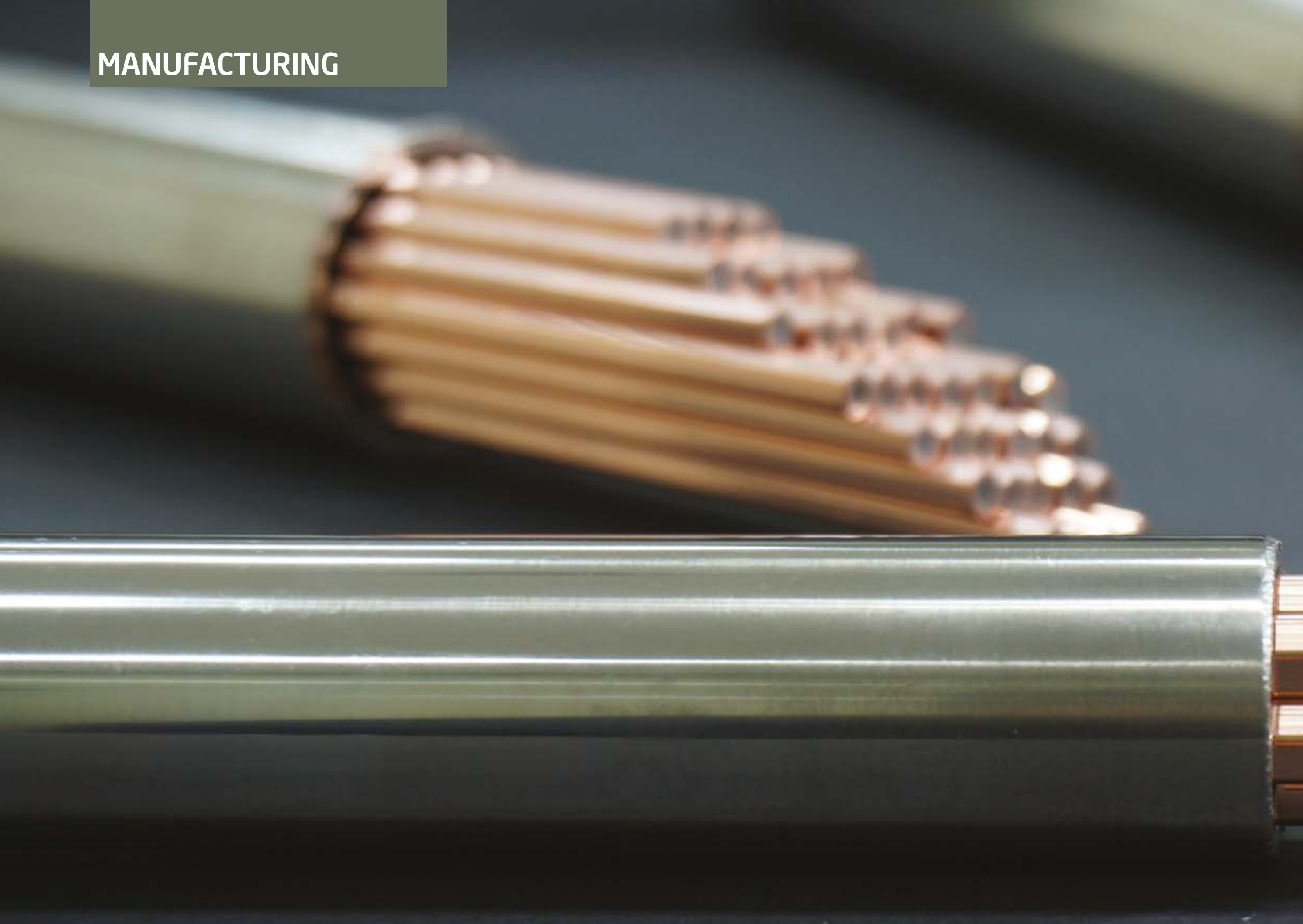

Status of MgB_2 superconducting wires at Sam Dong

Towards sustainable power and energy applications

ABSTRACT

MgB_2 superconducting wires have remarkable potential as cost-effective materials for transformers, generators, power transmission, and superconducting magnetic energy storage to enable highly efficient power-grid networks for sustainable development. Herein, we report multifilamentary MgB_2 wires with variously designed architectures that have been developed by Sam Dong Co., Ltd. The customized manufacturing process can also produce long-length pieces up to 3 km in length, indispensable in constructing large-scale devices, including cables. Based on this progress, we will continue to develop high-performance MgB_2 wires and related superconducting technologies.

KEYWORDS:

critical current density, MgB_2, multifilamentary, superconductor, wire

1. Introduction

In recent years, newly developed energy systems have come into widespread use in our daily lives. More energy-efficient solutions with ecological adaptation have also been prioritized towards sustainable societies. Since 2001, with the discovery of superconductivity, magnesium diboride (MgB_2) has been considered the most promising candidate in terms of cryogen-free operation, replacing conventional low-tempera-

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Sam Dong Co., Ltd. has scaled up and customized manufacturing processes for MgB_2 superconducting wires with variable structural designs and for their mass production

ture superconductors, niobium titanium (NbTi) and niobium tin (Nb_3Sn), because of the relatively high critical temperature of 40 K [1]. In particular, MgB_2 composite conductors are capable of enormous current flow in direct or alternating current operation without Joule heating or with small losses, respectively. In a dry cryostat (i.e., Gifford-McMahon cryocooler), the superior features offer potential for the creation of new innovative technologies. In fact, MgB_2 superconducting applications have now moved beyond the research stages into prototypes and commercial products. When compared to conventional superconducting wires, NbTi and Nb_3Sn, which have been produced and used worldwide, there are, however, still impediments to the availability of structural varieties in multifilamentary forms for long-length conductors. The immature and limited manufacturing technology is a major barrier to utilization in much wider practical applications. In this article, we report customized manufacturing systems for various multifilamentary conductors and introduce the MgB_2 wire products that have been developed so far at Sam Dong Co., Ltd.

2. The Sam Dong MgB_2 wires

2.1 Customized manufacturing and evaluation systems

Sam Dong Co., Ltd. (hereafter, Sam Dong) [2], Republic of Korea, was established in 1977 to produce oxygen-free high conductivity (OFHC) copper (Cu), continuously transposed conductor (CTC), copper strip, various copper shapes, and insulated rectangular and round wires (enamel, paper, glass yarn, etc.). Sam Dong has also established entities in Tennessee and Ohio in the USA and Kostrzyn nad Odra, Poland, to meet overseas customers' demands efficiently. Thus, our company is supplying the highest quality products and services for heavy industries in North and South America, Europe, Asia, and Oceania.

In addition to these corporate activities, we established the Daejeon R&D Center in 2015 to initiate the manufacturing of MgB_2 superconducting wires in collaboration with Kangwon National University and Korea Atomic Energy Research Institute, Republic of Korea, and University of Wollongong, Australia. For the development of the manufacturing system, we have selected powder-in-tube (PIT) processes. These methods are known to enable the fabrication of kilometre-scale composite wires with reliable superconducting performance. To date, we have devoted efforts to scaling up and customizing the manufacturing process for variable structural designs and their mass production. Figs. 1(a) and (b) show the commercial-scale manufacturing capability. Our facility is equipped with a linear draw bench and a circular bull block. The former can linearly pull a composite rod or wire up to 25 m in length through a reducing die. The latter is operated with a 1.5 m diameter capstan drum to draw and reel a composite wire. The combination of these drawing processes with rotary swaging (Fig. 1(c)) can thus be applied for scalable production of MgB_2 wires. The mechanically deformed composite conductors are then evaluated in terms of their transport critical current capability (Fig. 1(d)), which is the most important criterion for industrial superconducting applications.

Figure 1. Our facilities for commercial-scale wire production and measurement: (a) a 25 m linear drawbench; (b) a bull block equipped with a 1.5 m diameter capstan drum; (c) a 20-horsepower rotary swaging machine; (d) measurement systems for electromagnetic properties of superconducting wires.

2.2 An integrative approach to various structural designs

A superconducting system is known to suffer from thermal stress in the cryogenic environment and magnetic stress created by the Lorentz force. To ensure mechanical stability, it was thus necessary to estimate the total combined stress (thermal and magnetic). It is well known that multifilament wires, including 6 to 54 filaments inside the outer metallic tube, have a higher tensile strength and robust bending strain compared to monofilament wires. Moreover, such a feature can apply to twisted or braided features without any mechanical fracture for specific aims, i.e., power transmission cable and energy storage system. To design and produce multifilamentary conductors, the PIT process is applied

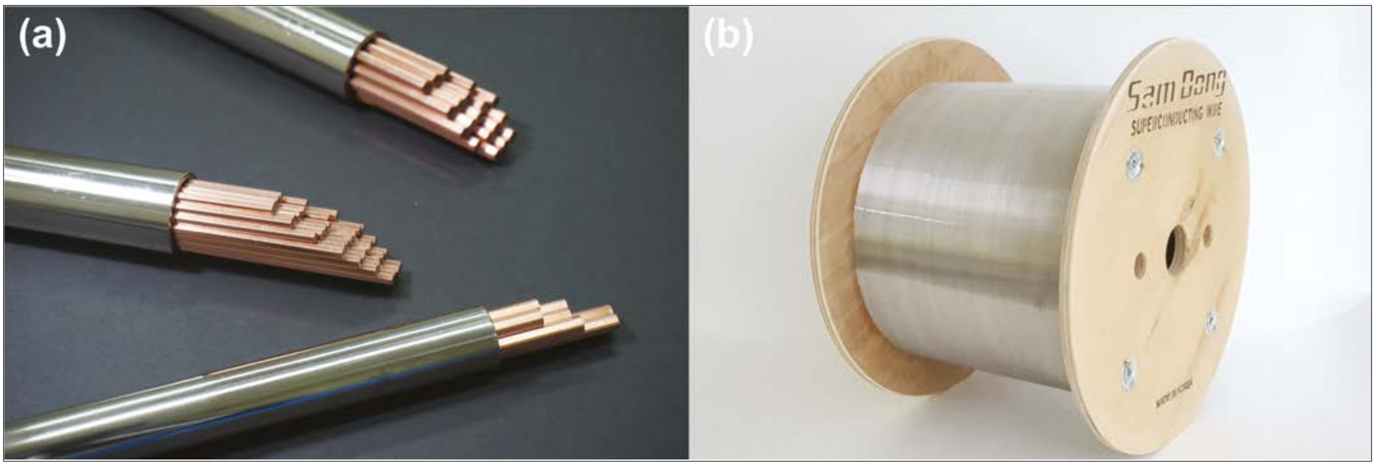


Figure 2. Photographs of (a) filaments stacked wires and (b) 1 km-scale commercial MgB_2 wire

as mentioned above. MgB_2 / metal composite materials are inserted and stacked into metal jackets, as shown in Fig. 2(a). The cross-sectional designs are customized by changing the filament number, size, shape, position, and composition of the stacked composites, depending on the specifications required for individual superconducting applications. The assembled bundles can then be drawn into multifilamentary wires as desired products. Fig. 2(b) shows an 18-filament MgB_2 / Nb / Cu / Monel composite wire as an example of our final product, which is 1 km in length and 0.83 mm in diameter. The multifilamentary conductor can be produced without any fracturing of the wire during all mechanical deformations.

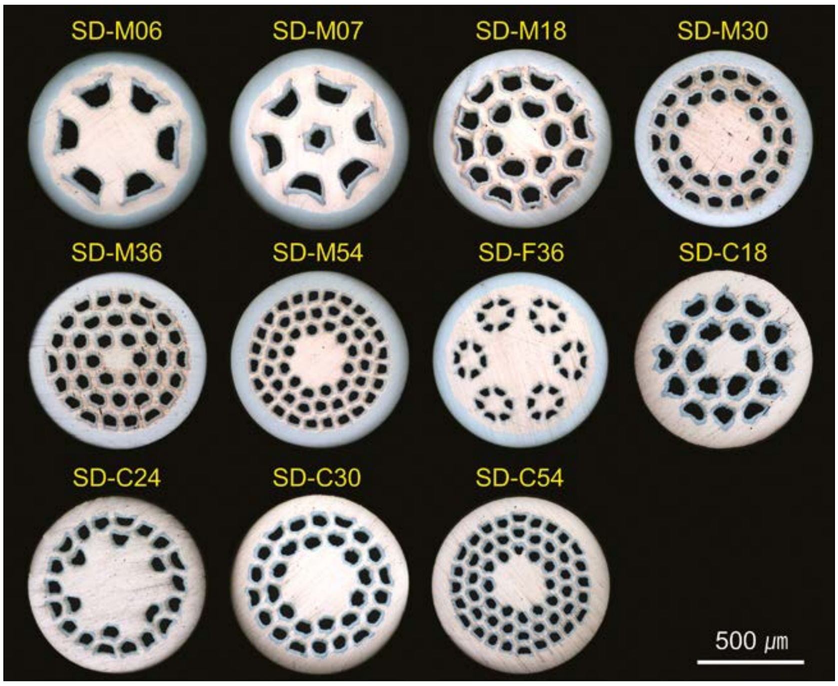


Figure 3. Cross-sectional views of various commercial MgB_2 wires produced by Sam Dong

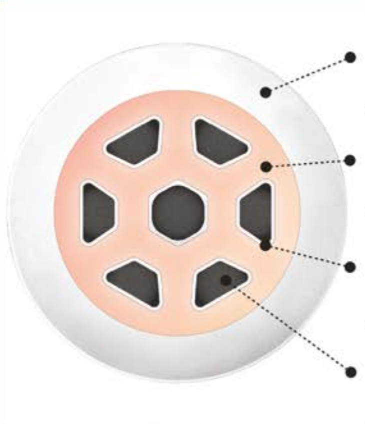
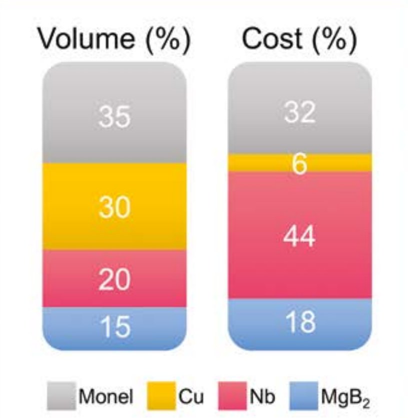
Cross-sectional structures of our final products are shown in Fig. 3. The wire specifications are also listed in Table 1. Many different architectures are addressed to meet our customers' requirements. The aims of various wires are to consider electrical, mechanical, and thermal properties. For the purpose of increasing the mechanical stability of the wire, the copper outer sheath can be replaced by Monel (Ni-Cu alloy) or GLIDCOP™.

This Monel sheath offers the benefits of lower resistivity without sacrificing a significant degree of the strength needed for mechanical deformation, especially in the drawing. However, to further enhance the thermal stability, we need to increase the area fraction of the copper in the wire. In terms of current carrying capacity, the architecture of multifilamentary wires prefers to be considered to increase an active superconducting area. The composites mainly consist of Monel, Cu, Niobium (Nb), and MgB_2, as can also be seen in Table 2.

Table 1. Detailed specifications of various commercial MgB_2 wires produced by Sam Dong

Wire	Filament No. (ea.)	Diameter (mm)	Outer sheath	Compositional area fraction (%)			
				Monel	Cu	Nb	MgB_2
SD-M06	6	0.83	Monel	32	48	11	9
SD-M07	7	0.83	Monel	34	44	12	10
SD-M18	18	0.83	Monel	33	30	21	16
SD-M30	30	0.83	Monel	33	31	23	13
SD-M36	36	0.83	Monel	32	23	29	16
SD-M54	54	0.83	Monel	35	29	21	15
SD-F36	36	0.83	Monel	30	52	12	6
SD-C18	18	0.83	Cu	-	64	21	15
SD-C24	24	0.83	Cu	-	74	15	11
SD-C30	30	0.83	Cu	-	65	21	14
SD-C54	54	0.83	Cu	-	62	24	14

Table 2. The structure of MgB_2 superconducting wire, the role of composition, and the price per each composition

Cross-sectional image of MgB_2 superconducting wire	Material	Role	Cost per unit of volume
	Monel	• Outer sheath • Enhancement of mechanical property	
	Cu	• Inner sheath • Achievement of electrical and thermal stabilities	
	Nb	• Diffusion barrier • Prevention of chemical reaction between Mg and Cu	
	MgB_2	• Superconductor • Transport current	

Depending on specifications required for individual superconducting applications, copper stabilizer fractions and the number of superconducting filaments in MgB_2 multifilamentary superconducting wires can be substantially modified in our commercial-scale manufacturing system

Monel is applied to enhance the mechanical properties of the superconducting wires and also achieve a relatively low ferromagnetic loss compared with typical magnetic materials such as iron and nickel, which are often used as an outer metal sheath for conventional MgB_2 conductor. Nb is used as a chemical barrier that prevents a reaction between the precursor (for the MgB_2 phase) and the Cu metallic layer. Cu is well known as an excellent forming / conductivity material that offers stable performance and operation in superconducting applications. Moreover, it is a key component in a cryogenic environment from the viewpoint of thermal stability. The stabilizer fractions in the multifilamentary wires can be controlled and increased up to 74 % (area fraction). The maximum number of superconducting filaments that currently can be fabricated is 54, and a further increase is expected. Furthermore, enormous improvement of the electrical properties can be achieved with optimal architectures.

Table 3. Characteristic comparison among superconducting materials, NbTi, Nb_3Sn, $REBa_2Cu_3O_{7-x}$ (where RE = Y and Gd), $Bi_2Sr_2CaCu_2O_{8+\delta}$, and MgB_2

Material	Low-Temperature Superconducting wires		High-Temperature Superconducting wires		
	Nb-Ti	Nb_3Sn	$REBa_2Cu_3O_{7-\delta}$	$Bi_2Sr_2CaCu_2O_{8+\delta}$	MgB_2
Discovery of superconductivity	1950's	1950's	1980's	1990's	2000's
Critical temperature (K)	9	17	89	108	39
Cryo-system	LHe*		LN_2* or Cryocooler		LH_2* or Cryocooler
Operating cost	Very high	Very high	Very low	Very low	Low
Conductor cost	Very low	High	Very high	High	Low
Cost driver	Material (Nb)	Material (Nb)	Capital plant	Material (Ag)	Material (Nb)
Critical current density (A/mm^2)	2×10^3 (4.2 K, 10 T)	2×10^3 (4.2 K, 15 T)	4×10^5 (4.2 K, 5 T)	1×10^4 (4.2 K, 5 T)	2×10^3 (4.2 K, 5 T)

*LHe, LN_2, and LH_2 are abbreviations for liquid helium, liquid nitrogen, and liquid hydrogen, respectively.

MgB_2 superconducting wires are expected to be widely used as advanced materials for various innovative applications, for example, large-scale power grids, renewable 10 MW offshore wind turbine generators, and hybrid energy storage systems combined with SMES for stable power-grid networks towards sustainable development

2.3 Transport critical current performance

The traditional method to evaluate current carrying capabilities of low- and high- temperature superconductors is by its immersion in a bath of liquid helium (LHe), generally at 4.2 K. Fig. 4(a) shows the field dependence of the transport critical current density (J_c) at 4.2 K (in an LHe) for our multifilamentary MgB_2 wires. The J_c was calculated by dividing the critical current by the cross-sectional area of the MgB_2 core. The J_c performance of wire products recently developed by other suppliers was also reported in the literature [3-5], and these values are plotted for comparison. All the MgB_2 wires were commercially manufactured through either an *in-situ* or *ex-situ* PIT process. The former and latter are methods of manufacturing wires by using unreacted Mg + 2B powder mixtures and pre-reacted MgB_2 powders, respectively. Since carbon (C) is widely used as a dopant to improve the high-field transport property, doped wires are also compared. The critical current performance of our manufactured wire is found to be comparable to that of the other products. In addition, the transport J_c properties for the undoped wire at 10, 20, and 25 K are shown in Fig. 4(b). The development of further approaches, especially with carbon doping, to enhance the in-field performance at different temperatures is now in progress.

3. Future potential applications of MgB_2 wires

A notable advantage of using MgB_2 instead of conventional materials such as NbTi and Nb_3Sn is its suitable operating temperature for superconducting applications. As can be seen in Table 3, the critical temperature of the MgB_2 superconductor is much higher than that of the Nb-based materials. In particular, since the boiling point of hydrogen is about 20 K, utilization of the element as an indirect (i.e., dry-cryocooler) or direct cooling (i.e.,

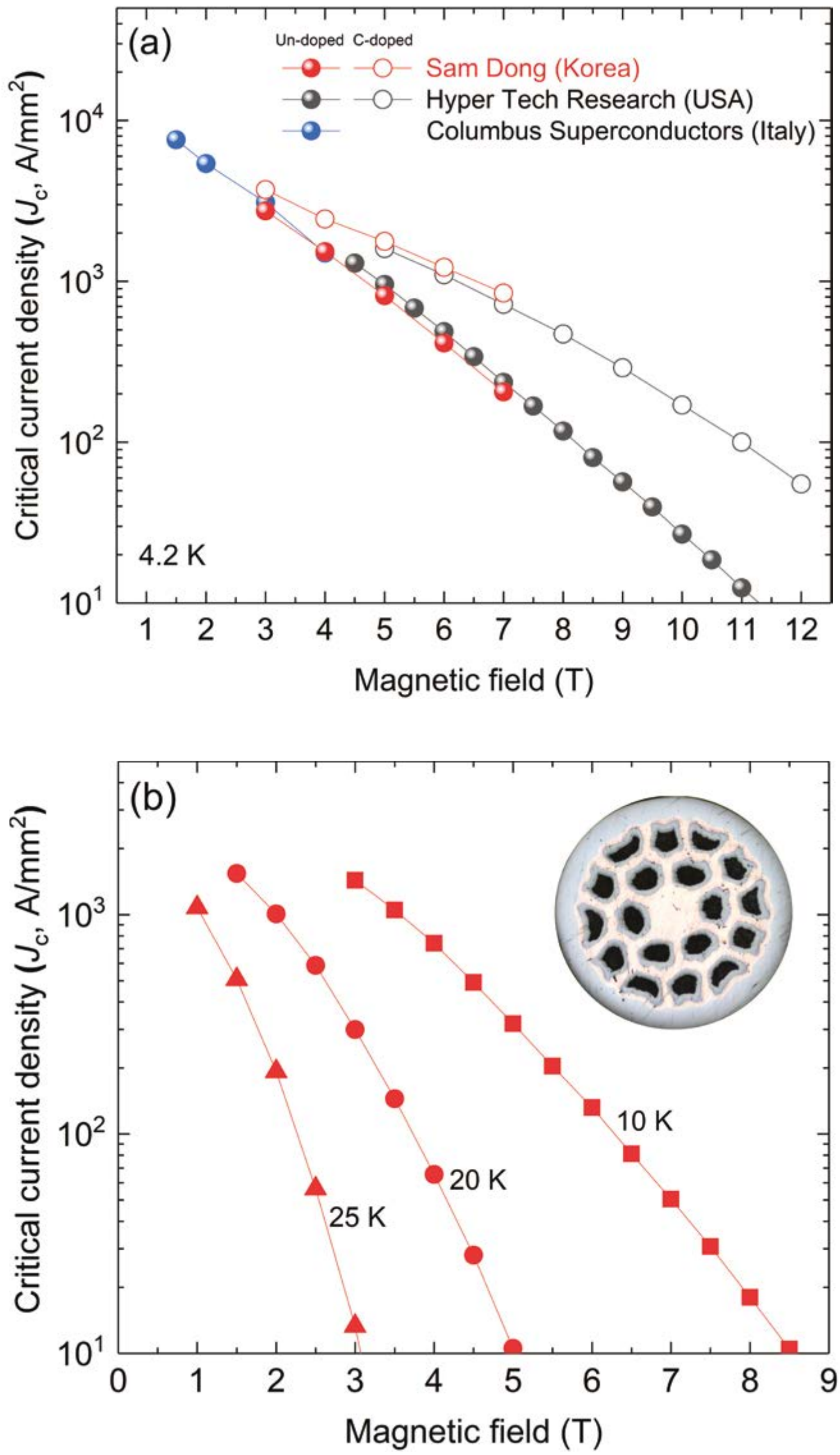


Figure 4. (a) Comparison of the critical current density of MgB_2 wires among various suppliers: Sam Dong (Korea), Hyper Tech (USA) [3, 4], and Columbus (Italy) [5]; (b) Magnetic field dependence of critical current density of undoped MgB_2 wire produced by Sam Dong at 10, 20, and 25 K. The measurement was carried out at the University of Wollongong, Australia.

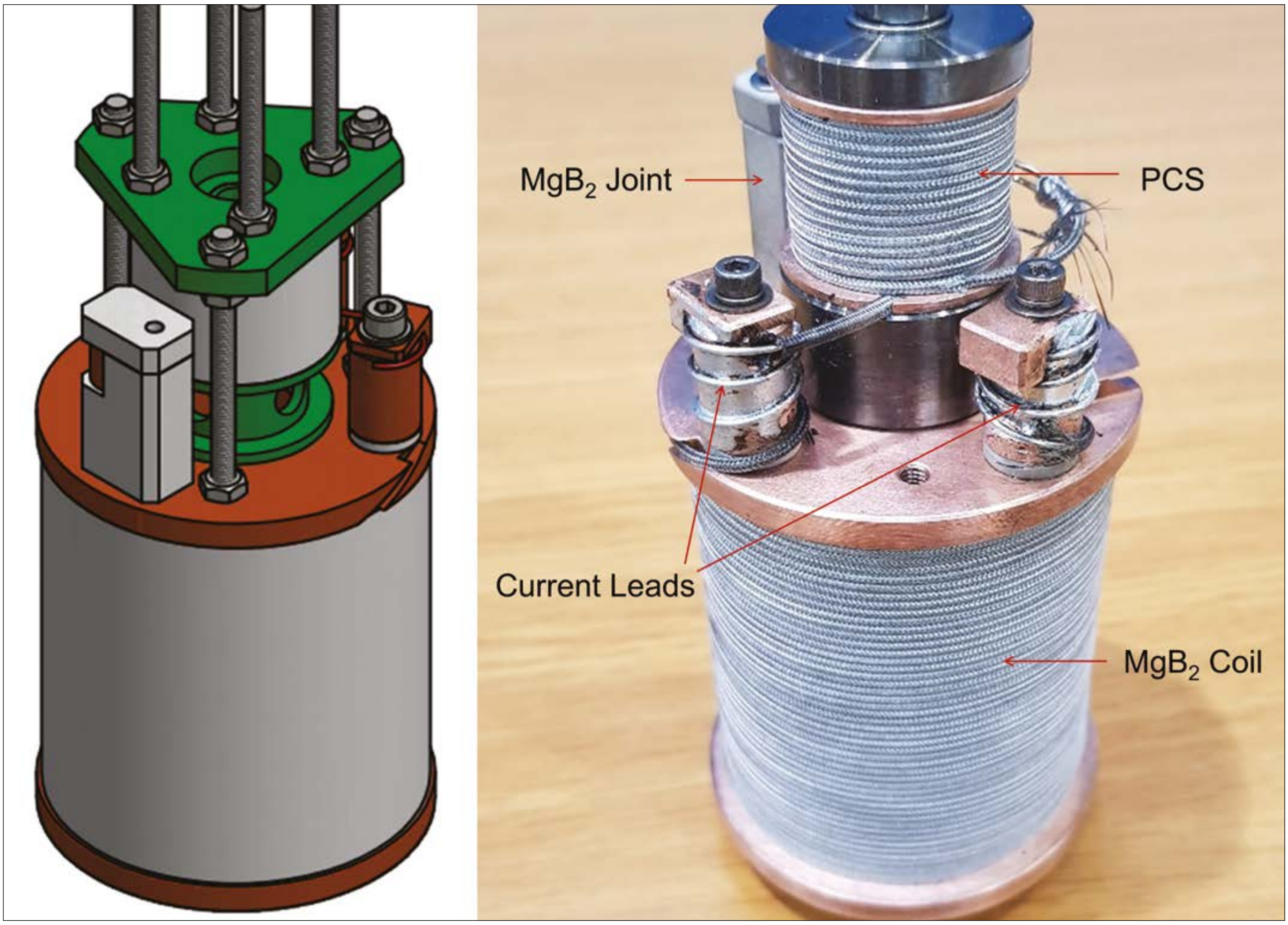


Figure 5. MgB_2 coil with persistent-current switch manufactured using Sam Dong's 19-multifilamentary MgB_2 wires in Kangwon National University and Kyungpook National University, Republic of Korea

Sam Dong Co., Ltd. will continue to develop more cost-effective MgB_2 superconducting wires and related application technologies for more energy-efficient systems and solutions

wet-cryogen) medium has emerged as a sustainable approach for future superconducting technologies.

An example would be smart energy management systems that employ superconducting magnetic energy storage (SMES), which can be utilized in hydrogen stations for fuel cell vehicles [6]. The superconducting devices are combined with an electrolyser, fuel cell, and hydrogen storage. The advantages of SMES and the other storage unit are well known to be high power density with fast response and high energy density, respectively. Thus, the hybrid energy storage system can serve as a stabilizer for the output of renewable power and act as an efficient buffer between electricity demand and supply towards more stable grid systems. In addition to hydrogen-based systems, the excellent superconducting property of MgB_2 also offers research and development opportunities for innovative energy applications, including large-scale power grids across Europe [7], renewable 10 MW offshore wind turbine generators [8], and advanced nuclear fusion reactors based on the International Thermonuclear Experimental Reactor (ITER) [9]. A high-temperature superconductor MgB_2 is competitive against YBCO ($YBa_2Cu_3O_{7-\delta}$, YBCO) thin film for magnets operating at less than 5 T and at 10-15 K. Owing to operational cost advantage, the MgB_2 superconductor has emerged as a serious contender to YBCO for magnet applications. The MgB_2 has some advantages over YBCO that are crucial for the commercial proliferation of various applications. These include as follows: i) MgB_2 is available as round wire or square conductor, which generally produces better field homogeneity than any other conductor form, especially thin film or tape; ii) in anisotropy-free round wire, the *n*-value (sharpness of superconducting transition) is generally larger than that in tape; iii) in terms of performance to price ratio, MgB_2 surpasses YBCO; and iv) the operating temperature in the 10-15 K range is readily achievable with a cryocooler.

4. Challenges and future plans

This article has described our customized production of MgB_2 materials and multifilamentary wires along with their critical current performance. Toward practical usages, we are also focusing on superconducting joint techniques with magnet designs to enable persistent-mode operation (zero resistance). A test product fabricated through a collaborative study is shown in Fig. 5.

Very recently, a superconducting coil was designed with s-glass insulation and constructed with an MgB_2 joint and a persistent-current switch (PCS) by using 19-multifilamentary MgB_2 wires in our company. In persistent mode, the superconducting coil and PCS are connected in parallel. The PCS would considerably reduce the operational cost of the system and heat input into the cryostat to produce an ultra-stable magnetic field. Depending on the required needs for technological demonstration and applications, we will continue to customize the wire specifications and enhance the critical current capabilities.

In addition to the wire performance, insufficient price competitiveness is one of the most significant limitations to various superconducting applications, especially compared with NbTi wires (Table 3). The main driver of the material cost for multifilamentary MgB_2 wire is Nb, which functions as a chemical barrier during the sintering process. Even if the proportion of Nb to the total volume is only 20 %, the chemical protection cost accounts for 44 % of the total material cost, as shown in Table 2. Accordingly, an alternative barrier or method is important to fabricate and supply commercial superconducting wires at an affordable price. We are currently developing optimal ways to alter or remove the expensive Nb barrier from the multifilamentary designs and to produce more cost-effective MgB_2 wires by using our customized manufacturing system.

For future alternative current (AC) applications, AC loss needs to be considered. Total AC losses are known to consist of hysteresis, coupling, and eddy-current losses. Hysteresis losses can be reduced by the filament size. Coupling losses can be minimized by filament twisting. Finally, eddy-current losses can be reduced by increasing metallic matrix resistivity. To complete this target, we further look into our wire architectures.

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Ju Heum Jeon is a Research Director of the Sam Dong R&D center and a Vice President of Sam Dong Co., Ltd., Republic of Korea. For over 45 years, he has worked on various copper wires, and then served as the general manager. He brings vast experience of international collaboration with various industries, institutes, and customers. His current research is focused on commercial MgB_2 superconducting wires for energy application.

Ee Joo Lee is a founder and CEO of Sam Dong Co., Ltd., Republic of Korea, Europe, and America. At Sam Dong Co, Ltd, he has continued to invest next-generation superconducting conductor as well as expanding into other energy systems and solutions.