Development of High-Temperature Superconductor Magnets Capable of Generating a High Magnetic Field

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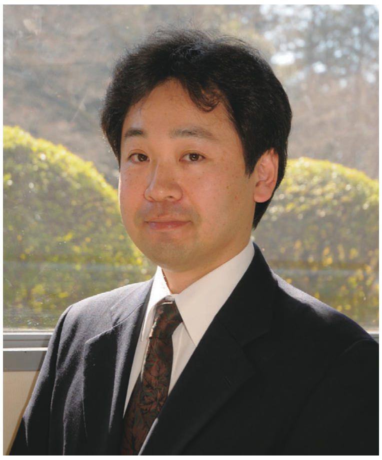

Until now, the problems of mechanical strength and thermal stability have created a bottleneck for the practical application of high-temperature superconductor bulk magnets. These problems have been resolved using new technology, and as a result, a high-temperature superconductor has been successfully made to generate a magnetic field of 17.24 tesla, the highest level achieved in such a material (Fig. 1). This research was published in the British scientific journal *Nature* 421, 517-520 (see http://www.nature.com/nature/journal/v421/n6922/full/nature01350.html), and has attracted worldwide attention.

As the intensity of the magnetic field generated in a bulk superconductor increases, the superconductor itself is subjected to an increasing electromagnetic force that imposes a growing load on its material strength. This is a serious problem, and the intensity of the magnetic field generated can even rise as high as the strength limit. Bulk superconductors have a large thermal expansion coefficient together with low thermal conductivity. The material they are composed of is also highly anisotropic, which makes it fracture easily. Consequently, a tensile stress is generated between the interior and exterior of the sample during the cooling phase of fabrication. The result is that microcracking occurs. These cracks had been thought to reduce the strength of the superconductor, and they did not diverge from the estimated range.

A method was devised to impregnate bulk superconductors with epoxy resin in a vacuum, and it has been confirmed to be capable of dramatically improving their mechanical properties. Thanks to this discovery, the mechanical strength has been enhanced dramatically and the generated magnetic field has also been upgraded. When an attempt was made to trap an extremely high-intensity magnetic field, however, it was found that the material would break down at about 14 tesla, regardless of the increased mechanical strength. Testing was done to measure the heat generated in the interior of the superconductor in conjunction with a particular phenomenon known as flux jump that occurs with superconductivity. It was demonstrated that the generation of this heat causes bulk superconductors to become normal conductors that are unable to trap a high magnetic field. Attempts to make the bulk superconductor trap a field cause quantized flux to penetrate from the exterior to the interior of the superconductor, and the movement of this flux necessarily results in the generation of heat. There is no problem if this heat can be quickly removed by an exterior coolant. If the heat continues to be generated, however, the temperature will rise locally. The result is that the rise in temperature is accompanied by a sudden drop in superconductivity, and the large electromagnetic force caused by sudden change in the magnetic field eventually destroys the magnet itself. This thermal instability of bulk superconductors is due to their low thermal conductivity. Poor heat transfer causes heat to pool inside the superconductor, the superconductivity breaks down, and the superconductor becomes unable to trap a magnetic field. Therefore a hole was drilled at the center of a bulk superconductor that had been previously impregnated with resin, and metallic aluminum, which has high thermal conductivity, was introduced into the hole. The superconductor was then impregnated with an alloy with a low melting point (Bi-Pb-Sn-Cd: melting point 100–105°C) in order to conduct heat and raise the thermal conductivity (Fig. 2). The low-melting-point alloy infiltrated the cracks inside the superconductor and yielded a very efficient heat transfer characteristic. Allowing heat to escape from the interior limits the pooling of heat and realizes thermal stability in the bulk superconductor. In a synergistic effect with the resin impregnation, which improves the strength, the high-temperature superconductor was able to generate an extremely high magnetic field exceeding 17 tesla. This technique of resin impregnation and metal impregnation of bulk superconductors has been highlighted for potentially broad practical application as a rational method for increasing strength and thermal stability in order to improve magnetic field generation. The technology is being used in Japan and other countries in the development of such applications as current leads for use in Maglev, flywheels (power storage), nuclear magnetic resonance (NMR), magnetic resonance imaging (MRI), superconducting motors, magnetic separators, and permanent current switches (PCS).

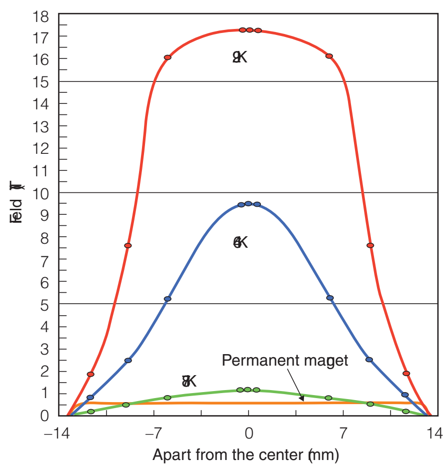

Fig. 1 The field distribution trapped by bulk superconductors with impregnation technique

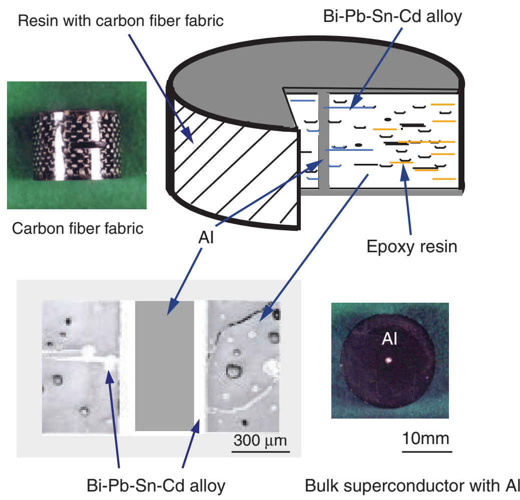

Fig. 2 Structure and optical micrographs of bulk superconductors for high trapped-field