Self-bonding NbTi Wires for Superconducting Coils

1. INTRODUCTION

During the manufacturing process, superconducting coils are fabricated by winding an insulated superconducting wire into a coil and impregnating it with a curable epoxy resin to secure the superconducting wire in place. This suppresses the movement of the wire due to the electromagnetic force when the coil is energized and prevents quenching, which occurs when the conduction state changes from superconductivity to normal conductivity. However, the epoxy resin impregnation process involves multiple steps, including vacuum impregnation to minimize voids within the resin and to ensure sufficient adhesive strength. Additionally, the generation of epoxy waste during the manufacturing process presents an issue.

To address these challenges, we have developed a NbTi superconducting wire that is pre-coated with self-bonding resin, which eliminates the epoxy impregnation process. This development will greatly simplify the manufacturing process of superconducting coils. Furthermore, the bonding functionality of self-bonding wire is expected to improve the flexibility in coil design and enhance the convenience of winding work.

2. FEATURES OF SELF-BONDING NbTi SUPERCONDUCTING WIRES

As shown in Figure 1, the self-bonding NbTi superconducting wire possesses a unique feature that enables the wires to bond together through a simple heat treatment process after coil winding. This is achieved by incorporating an outermost layer composed of a fusible resin on the insulation layer. This approach offers significant advantages in terms of simplifying the manufacturing process of superconducting coils and eliminating resin waste. Table 1 provides an overview of the coating materials and dimensions for the self-bonding NbTi superconducting wire. For the insulation layer, we use polyvinyl formal (PVF), a commonly employed insulation coating material. As for the fusible resin, we selected a material that can be fused at a low temperature of 200°C or less. Through material modification, we conducted research to enhance the mechanical properties of the material and achieve excellent bonding strength. As a result, we developed a phenoxy resin composition that meets the required properties. As indicated in Table 1, the insulation layer and self-bonding layer have thicknesses of 0.03 mm and 0.04 mm, respectively.

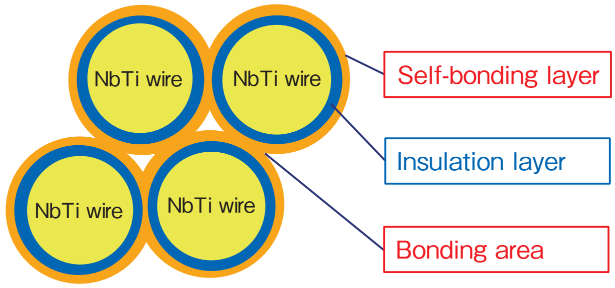


Figure 1 **Schematic diagram of a self-bonding NbTi superconducting wire.**

Table 1 **Coating materials and dimensional data for self-bonding wire products.**

Item	Unit	Developed product (Self-bonding wire)
Insulation coating material	—	Polyvinyl formal (PVF)
Self-bonding material	—	Phenoxy based resin composition
Conductor diameter	mm	0.9 – 1.4
Insulation layer thickness	mm	0.03
Self-bonding layer thickness	mm	0.04
Outer diameter	mm	1.0 – 1.5

3. CHARACTERISTICS OF SELF-BONDING STRENGTH

The samples were fabricated in compliance with the Japanese Industrial Standard (JIS) 3216-3 helical coil method using the self-bonding NbTi superconducting wire. Subsequently, samples with different fusion conditions were made by varying the temperature and the holding time in a forced-blasting-air type oven. The bonding strength was evaluated by a vertical tensile test of the helical coil conducted with a tensile testing machine. Figure 2 shows the effect of the heat treatment temperature on the self-bonding strength. At a specific heat treatment time, the bonding strength tends to increase as the heat treatment temperature rises. For example, in the case of samples treated for 2 hours, the bonding strength was 6.2 N at 130°C, and it was observed to increase to 9.4 N at 195°C. It is thought that the increase in strength with higher heat treatment temperature is related to the temperature dependence of the melt viscosity of the self-bonding material. The decrease in melt viscosity at higher temperatures facilitates resin flow, leading to an increase in bonding strength as a result of the increment of interfacial area between wires.

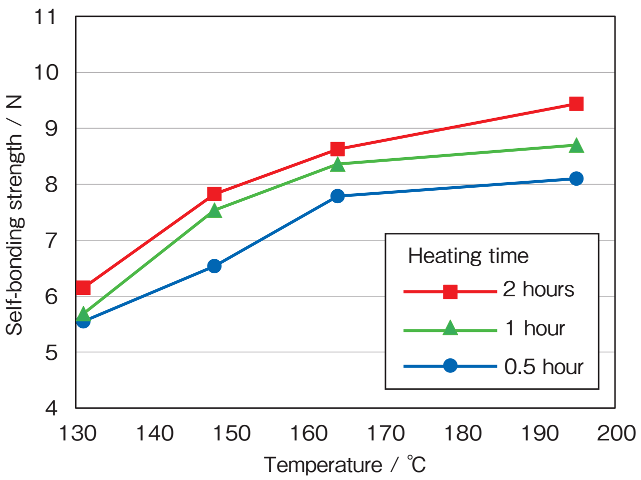


Figure 2 **Effect of the heating temperature change on the self-bonding strength.**

In actual coils, various materials are used in addition to the superconducting wire. Considering the heat resistance of these components, heat treatment at lower temperatures is preferable. Therefore, we selected a low-temperature condition of 148°C and a high-temperature condition of 195°C. Heat treatment was performed for a long period up to 16 hours, and the effect on the bonding strength was investigated (Figure 3). The results showed that the sample treated at 195°C exhibited high bonding strength for up to 2 hours, whereas the sample treated at 148°C showed higher bonding strength after 4 hours. It is speculated that the decrease in bonding strength after 4 hours or more of heat treatment at 195°C is associated with changes in the mechanical properties of the resin layer. On the other hand, under the conditions of 148°C, high bonding strength can be obtained even after 4 hours or more of heat treatment, and a value of 11.6 N achieved even after 16 hours of heat treatment. Based on these results, heat treatment at low temperatures for a long period is considered more effective for actual coils.

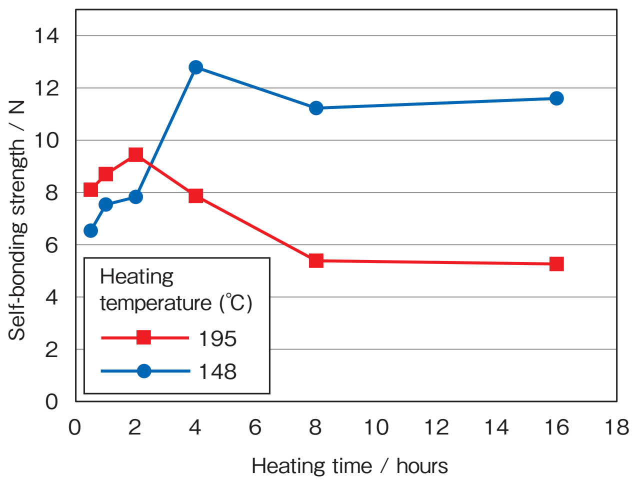


Figure 3 **Effect of heating period change on the self-bonding strength.**

4. CHARACTERISTICS OF THE SELF-BONDING COIL

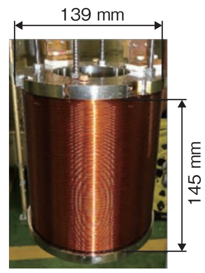
For the purpose of verifying the applicability of the self-bonding NbTi superconducting wire to the superconducting coils, we fabricated a coil using this wire and investigated the current conduction characteristics in the coiled state. Table 2 provides the specifications and the external appearance of the coil. The coil has an inner diameter of 100.3 mm, an outer diameter of approximately 139.7 mm, and a height of approximately 145.5 mm. The maximum electromagnetic force applied to the coil is 114 MPa at the innermost layer in the center of the coil.

We conducted a coil energization experiment and confirmed the following results (Figure 4).

(1) Upon the first energization, the coil quenched at 380 A (load factor: 96%), while the second energization reached the wire critical current (I_c) of 391 A, achieving a load factor of 100%.

(2) After returning to room temperature, the coil was cooled down again and subjected to another current test. It did not quench and reached 391 A, similar to the previous test.

Table 2 **Specifications and a photo for a self-bonding coil.**

	Self-bonding coil
Coil configuration	Solenoid
Coil inner diameter (mm)	100.3
Coil outer diameter (mm)	139.7
Coil height (mm)	145.5
Total turn frequency	2580
Number of layers	20
Overview	

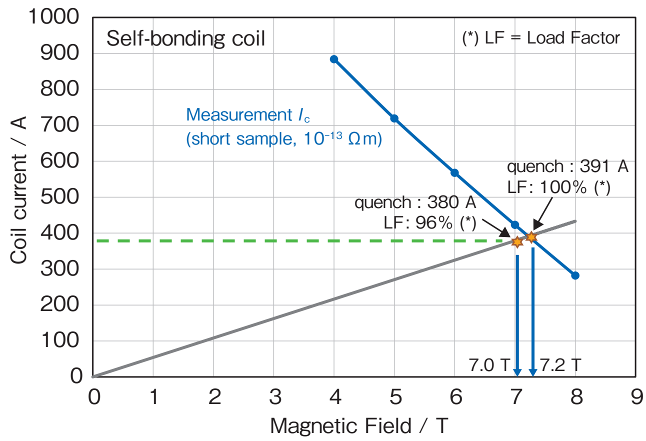


Figure 4 **Results of electrical current tests for a self-bonding coil.**

The self-bonding NbTi superconducting wire achieved a load factor of 100% after one training quench at a high load rate in the fabricated coil. Furthermore, it retained the previous energization history even when experiencing a temperature increase up to room temperature. Based on these results, we concluded that the self-bonding Nb-Ti wire is suitable for use in the fabrication of superconducting coil.

5. CONCLUSION

We have developed a self-bonding NbTi superconducting wire that eliminates the costly and time-consuming epoxy impregnation process used in the manufacturing of superconducting coils. By applying this product to commercial superconducting coils in the future, we aim to significantly improve productivity in the manufacturing while also contributing to the realization of environmentally friendly processes.

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