Cryogen-free superconducting magnet fabricated by a react-and-wind method employing Nb_3Sn wires with CuNbTi reinforcement

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Practical multifilamentary Nb_3Sn wires with CuNbTi reinforcement (CuNbTi/Nb_3Sn) exhibit the splendid mechanical tolerance of 340 MPa proof stress. We intended to develop a Nb_3Sn coil by a react-and-wind method for a wide bore cryogen-free superconducting magnet, and made a react & wind coil employing CuNbTi/Nb_3Sn wires. The performance test for the CuNbTi/Nb_3Sn coil was carried out, and the coil generated 2.2 T at 180 A as the individual test. In the combination test in a background field of 5.6 T, the react & wind processed CuNbTi/Nb_3Sn coil generated 7.5 T in a 220 mm room temperature bore. The wide bore cryogen-free superconducting magnet wound with highly strengthened CuNbTi/Nb_3Sn wires is now being used for a high field heat-treatment equipment at 7 T. This wide bore furnace provides special heat-treatment conditions of high temperature 1500 °C in fields up to 7.0 T in a 40 mm sample bore.

INTRODUCTION

A coil fabrication process for high field Nb_3Sn superconducting magnets usually adopts a wind-and-react (W&R) method, in which a coil wound with unreacted Nb-Sn wires is heat-treated for the Nb_3Sn compound reaction. This is because the reacted Nb_3Sn wire is very sensitive for stress and strain, and is apt to degrade the critical current due to the applied mechanical stress through a coil winding. However, it is impossible to construct a large Nb_3Sn coil like a nuclear fusion reactor coil by a W&R method. If we make possible to fabricate a react-and-wind (R&W) processed coil employing the pre-reacted Nb_3Sn wire, a heat-treatment process in a large furnace and an epoxy impregnation process in a large vacuum equipment can be eliminated. It is expected that the cost reduction due to the simplification of the coil fabrication process is very large. In particular, the time-related saving cost of the heat-treatment for the Nb_3Sn coil should be concentrated on.

On the other hand, we have developed a highly strengthened Nb_3Sn wire with an internal reinforcement of CuNbTi (CuNbTi/Nb_3Sn). A CuNbTi/Nb_3Sn wire reveals the strong proof stress of

340 MPa, even after the heat-treatment at 650 °C for 240 h [1]. This means that a CuNbTi/Nb_3Sn wire is 2-3 times as strong as a conventional Nb_3Sn wire with an ordinary copper stabilizer (Cu/Nb_3Sn). Therefore, a R&W method is now applicable for fabricating a Nb_3Sn coil employing highly strengthened Nb_3Sn wires.

This paper describes a cryogen-free superconducting magnet wound with pre-reacted CuNbTi/Nb_3Sn wires. A newly developed high temperature heat-treatment furnace combined with the wide bore cryogen-free superconducting magnet is introduced for an in-field process application.

CHARACTERISTICS OF HIGH-STRENGTH CuNbTi/Nb_3Sn WIRE

Figure 1 shows the fabrication process of high-strength CuNbTi/Nb_3Sn wires. The starting CuNbTi reinforcement was incorporated into the central area of a typical bronze-route Nb_3Sn wire, which is a so-called internal reinforcement process. After the heat-treatment at 670 °C for 200 h, the CuNbTi/Nb_3Sn wire has wire parameters such as the outer diameter of 1.0 mm, filament diameter of 3.5 μm, number of filaments of 9600, copper ratio of 26.3 %, and twist pitches of 32 mm, and reveals the critical current properties of 247 A at 12 T and 133 A at 15 T at 4.2 K. Although the CuNbTi/Nb_3Sn wire surely exhibits a strong proof stress of 340 MPa, it unfortunately has poor elongation properties in comparison with an another kind of high-strength Nb_3Sn wire with CuNb reinforcing composite [2]. This results in small shearing elasticity for CuNbTi/Nb_3Sn. In the R&W process, we may have to developed a new high-strength Nb_3Sn wire with a strong proof stress over 300 MPa and a good elongation property. However, the CuNbTi/Nb_3Sn wire does not reveal any degradation of the critical current for the repeated pre-bending treatment in bending strains up to 0.8 % and at 5 repeated times [3].

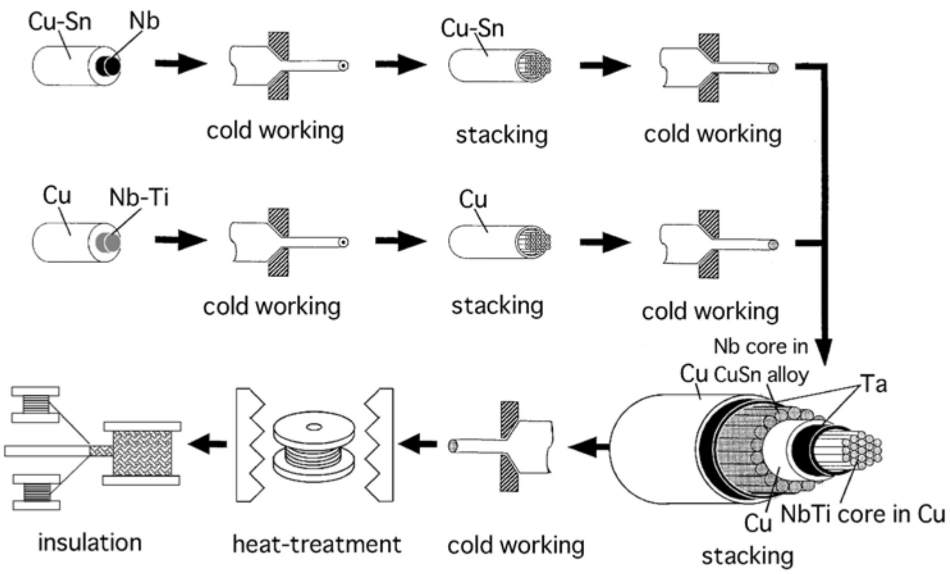

Figure 1 Fabrication process of a high-strength multifilamentary Nb_3Sn wire with internal reinforcement of CuNbTi composite.

In the R&W coil fabrication process, the pulleys with 300 mm in diameter and the coil bobbin with 260 mm in diameter, which correspond to bending strains below 0.4 %, were utilized. During the coil winding, the pre-reacted CuNbTi/Nb_3Sn wire was wrapped in polyimide insulation tape and the coil between windings was impregnated by epoxy resin. This proves that the R&W processed Nb_3Sn superconducting magnet no longer needs a coil heat-treatment furnace and a vacuum impregnation furnace for a reacted coil.

The R&W processed CuNbTi/Nb_3Sn coil, which has coil parameters such as 260 mm in inner diameter, 289 mm in outer diameter and 319 mm in height, was set into a background NbTi coil. The performance test was carried out as a cryogen-free superconducting magnet cooled conductively by GM-cryocoolers. Figure 2 shows the load line of the cryogen-free CuNbTi/Nb_3Sn superconducting magnet energized by using dual current supply system. The cryogen-free CuNbTi/Nb_3Sn insert coil quenched at a central field of 7.5 T at an operation current of 158 A in a 220 mm room temperature bore under the background field of 5.6 T. When the CuNbTi/Nb_3Sn coil was energized independently at currents up to 180 A as an individual test, the coil temperature rise due to ac loss was about 2 K. However, the temperature rise of the CuNbTi/Nb_3Sn coil was about 8 K due to the ac loss of the NbTi coil, when the outer NbTi coil was energized first. This means that there unfortunately exists a certain conduction cooling path with a poor connection in the CuNbTi/Nb_3Sn coil. The coil quench at 7.5 T may be related with Joule's heating at such a poor conduction cooling part in the background field of 5.6 T.

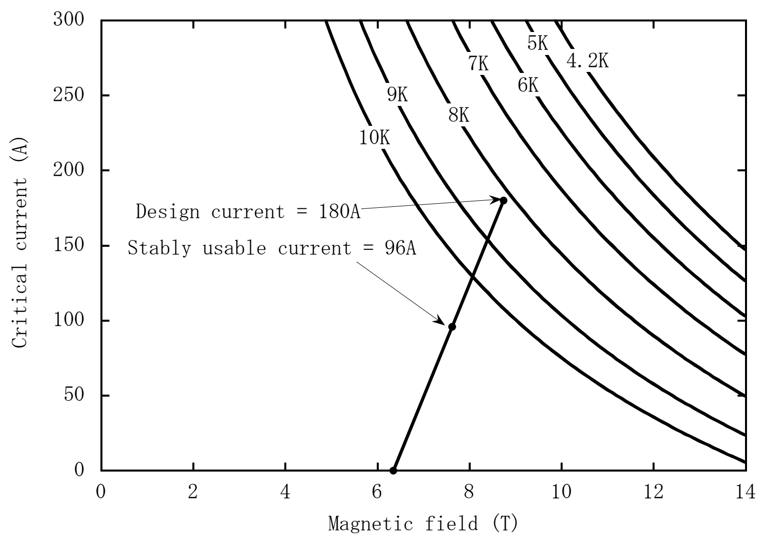

Figure 2 Temperature dependence of the critical current for CuNbTi/Nb_3Sn wire, and the load line of a CuNbTi/Nb_3Sn insert coil for the maximum field at the coil windings.

IN-FIELD HEAT-TREATMENT FURNACE AT 1500 °C AND AT 7 T

Figure 3 shows the high temperature heat-treatment furnace combined with the cryogen-free CuNbTi/Nb_3Sn superconducting magnet. The R&W processed CuNbTi/Nb_3Sn superconducting magnet is now being used for the in-field long-term heat-treatment at 7.0 T. A cylindrical heater was used to reduce an electromagnetic force applied for a wide bore heater in high fields. This furnace produces high temperatures up to 1500 °C in a flowing oxygen gas in fields up to 7.0 T. A heat-treated sample space with 40 mm in diameter and 50 mm in height is available within temperature homogeneity of 5 °C.

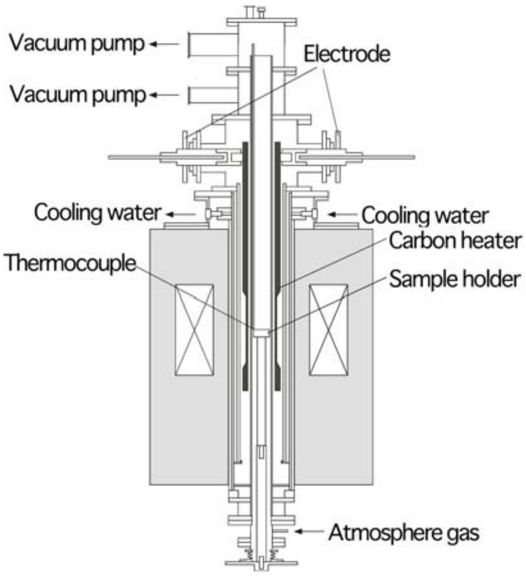

Figure 3 1500 °C high temperature heat-treatment furnace equipped with a 220 mm wide bore cryogen-free CuNbTi/Nb_3Sn superconducting magnet.

CONCLUSIONS

A react-and-wind method to fabricate a wide bore cryogen-free superconducting magnet was intended employing pre-reacted high-strength Nb_3Sn wires reinforced with CuNbTi composite. The react-and-wind processed CuNbTi/Nb_3Sn coil revealed a good performance and generated the total central field of 7.5 T in a background field of 5.6 T in a 220 mm room temperature bore.

A high temperature heat-treatment furnace combined with the newly developed CuNbTi/Nb_3Sn superconducting magnet was successfully demonstrated at 1500 °C in fields up to 7.0 T.

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