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Case Study of a 20 T-ϕ400 mm Room Temperature Bore Superconducting Outsert for a 45 T Hybrid Magnet

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***Abstract*—The High Field Laboratory for Superconducting Materials (HFLSM) and the Tsukuba Magnet Laboratory (TML) conducted in collaboration a case study on development of a 50 T-class hybrid magnet. To construct a high magnetic field magnet with compact and energy-saving design as well as with easy operation and maintenance, one has to develop high-strength Nb_3Sn strand cables, with maximized superconducting characteristics and which can withstand a large electromagnetic force over 500 MPa. For this purpose, the HFLSM has proposed and investigated the effect of repeated bending treatment (prebending) on Nb_3Sn strands internally reinforced with CuNb stabilizer leading to significant enhancement of the critical current density. In this report we present our results on application of the prebending effect to the development of high-strength strand cables. The designed prebent-strand cables are composed of three CuNb/Nb_3Sn strands ($3 \times \phi = 1.73$ mm) and four stainless steel strands ($4 \times \phi = 1.73$ mm). High-strength CuNb/Nb_3Sn strand cables have shown a stress limit of 552 MPa at 0.4% strain, and a critical current of $I_c = 1000$ A at 18.5 T and 2.0 K. For such high-strength strand cables, a 20 T superconducting magnet with a room temperature bore ($\phi = 400$ mm) consisting of five layers made of CuNb/Nb_3Sn and two layers of NbTi was designed. The coil parameters are: inner diameter $\phi = 440$ mm, outer diameter $\phi = 1332$ mm, coil height 1321 mm, inductance 350 H and magnetic stored energy 144 MJ at 908 A of the operation current. Winding of the coil was experimentally successfully simulated using dummy 3 + 4 strands cable composed of three Cu strands and 4 stainless steel strands with a similar design to the 3 + 4 strands superconducting cable presented above. The 20 T superconducting coil will be used as a 20 T outsert for a 25 T water-cooled resistive insert to obtain a 45 T hybrid magnet.**

***Index Terms*—High field facility, high magnetic field, hybrid magnet, superconducting magnet.**

I. INTRODUCTION

THE magnetic field is one of the most important thermodynamical parameters to study physical properties of the materials and the physical effects in general. In particular, a high magnetic field can be used as, or in extreme ultimate environments and, in the recent years, large progress in basic and application-oriented research employing high magnetic fields was obtained. Nevertheless, the demands to upgrade high magnetic fields not only to higher intensities but to achieve also a better accuracy and uniformity within large volume are priority issues. This explains initiation in the last several years, one after another, of the new programs for construction of high magnetic field facilities [1]–[3].

In Japan, a new pulsed magnet facility to attain a quasi-static field of 100 T for 0.1 s has been recently built in the Institute of Solid State Physics, The University of Tokyo, in collaboration with the Ultimate Science Research Center, Osaka University. This facility is aimed to be the starting point of a network for high magnetic field research. Both pulsed and static magnets will be included within this network that will promote research in advanced frontier science and will be useful for many outstanding scientific activities from around the world. Considering the strategic importance of high magnetic field research in the world, the High Field Laboratory for Superconducting Materials (HFLSM), Tohoku University and the Tsukuba Magnet Laboratory (TML), National Institute for Materials Science have decided to conduct in collaboration research on development of a 50 T-class hybrid magnet in Japan [4]. Worth to mention is that currently a 50 T hybrid magnet generating static fields is expected to consume an enormous power of 20 to 30 MW. This is not convenient especially in Japan where the cost of the electrical energy is high. To improve energy-saving and environmental issues related to generation of static fields by strong 50 T -class magnets, the construction plan of such magnets should adopt as a key strategy the improvement of the superconducting technology. Therefore, our aim is to fabricate a compact and energy-saving laboratory hybrid magnet with easy operation and maintenance. To succeed it is necessary to develop high-strength Nb_3Sn strand cables with high critical currents and good enough mechanical properties to withstand a large electromagnetic force over 500 MPa. In our study we shall use our previous experience, namely the newly developed fabrication process of the react-and-wind coils using prebent Nb_3Sn strands [5]. We have recently shown that the critical current greatly enhances when as-reacted Nb_3Sn strands are repeatedly bent at room temperature (prebending treatment) [6]. This critical current enhancement effect of CuNb/Nb_3Sn strands is related to improvement of the upper critical field and of the transition temperature due to relaxation of the thermal residual strain. Confirmation of the three-dimensional strain relaxation

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TABLE I
CuNb/Nb_3Sn STRAND CABLES

	3 strands	3+4 strands
strand diameter [mm]	1.0	1.0
nominal cable diameter [mm]	1.15	2.0
cabling pitch [mm]	48	63
curvature diameter [mm]	203	203
equivalent bending strain [%]	0.49	0.49

when pre-bending treatment is applied was obtained by direct neutron diffraction three-dimensional strain measurements on as-reacted and prebent CuNb/Nb_3Sn strands [7]. As a next development stage, application of the prebending effect to the development of high-strength strand cables is considered.

In this paper, the prototype test of the designed prebent-strand cables and their relevant characteristics to withstand large hoop stress are introduced. Using such high-strength strand cables, a 20 T-ϕ400 mm room-temperature-bore superconducting coil to be used as an outsert coil in the next fabrication-phase of the 45 T Japanese hybrid magnet is described as a case study.

II. HIGH-STRENGTH CUNB/NB_3SN STRAND CABLES

In order to investigate the application of the prebending effect to strand cabling process, two kinds of strand cables were fabricated by cabling the reacted CuNb/Nb_3Sn strands. Strands and cables were produced by the Furukawa Electric Company. As will be mentioned later, we intended to develop the $3 + 4$ strand cable consisting of three CuNb/Nb_3Sn strands and four stainless steel strands. The 3 strand cable composed of three CuNb/Nb_3Sn strands was also prepared for comparison.

As a first step, the strand-cable-samples of 3 strands and $3+4$ strands were fabricated without the prebending treatment.

Table I lists parameters for these cables. The fabrication process of the cables was the following: after fabrication of the CuNb/Nb_3Sn strand and final heat treatment at 750 °C for 96 h, strand was cabled using the cabling pitch P that is equivalent to a bending strain of $\varepsilon_{\mathrm{b}} = 0.4$-$0.5\%$. Using a spiral approximation model, the cabling pitch P was determined as $\mathrm{P} = 2\pi\mathrm{b}$, $\tan\alpha = \mathrm{R}/\mathrm{b}$ and $\kappa = \sin^2\alpha/\mathrm{R}$, where the nominal radius of a strand cable is R, the cable angle is α, and the curvature radius is κ. The equivalent bending strain ε_{b} for the CuNb/Nb_3Sn strand with strand diameter d is given by $\varepsilon_{\mathrm{b}} = (\mathrm{d}/2\kappa) \times 100$.

Fig. 1 shows the measured critical currents for the 3 and $3+4$ strands cable without application of prebending. The critical current values at 4.2 K for the 3 and $3+4$ strands are 959 A and 878 A at 10 T, 788 A and 744 A at 11 T, and 651 A and 613 A at 12 T, respectively. Comparing experimental values with the calculated total critical current values of 984 A at 10 T, 828 A at 11 T, and 669 A at 12 T for a cable with three CuNb/Nb_3Sn strands, the obtained values are reduced by about 3% for 3 strands and by about 10% for $3+4$ strands. This critical current reduction seems to be due to the unbalanced current flow for the strand cables and it can be compensated by applying before cabling a prebending treatment to the as-reacted CuNb/Nb_3Sn strands. As already mentioned, prebending treatment significantly improves superconducting characteristics of the strand.

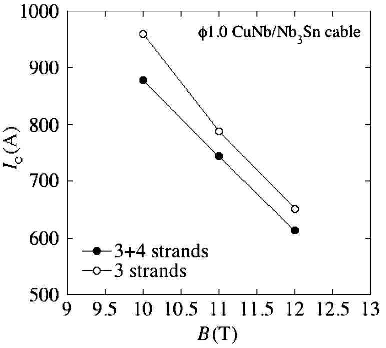

Fig. 1. Critical current in magnetic fields for 3 strand and $3 + 4$ strand cables from Table I.

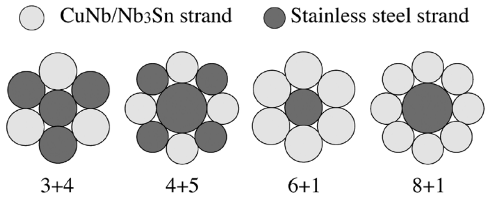

Fig. 2. Schematic cross section of high strength strand cables composed of CuNb/Nb_3Sn strands and stainless steel strands.

III. DESIGN OF A 20 T-ϕ400 MM ROOM TEMPERATURE BORE SUPERCONDUCTING OUTSERT

For the design of our 20 T superconducting outsert with a $\phi =$ 400 mm room-temperature bore, we adopted the tolerance level of 0.4% uniaxial strain for a CuNb/Nb_3Sn strand, which corresponds to the tolerance level of 220 MPa using the Young's modulus 56 GPa for a CuNb/Nb_3Sn strand [8]. The outer diameter of CuNb/Nb_3Sn strand was selected to be less than 2.2 mm. This diameter resulted from the rich experience on fabrication of the strands and from the necessity to obtain an operation current of 1000 A at 2.0 K. Being a multilayer coil configuration, a 5 mm gap between layer coils and a 50 μm thick layer insulation were adopted as design values.

The design optimization of the mechanical strength and of the critical current for the CuNb/Nb_3Sn strand cables was controlled by the use of stainless steel strands with 200 GPa Young's modulus. In the case of $4 + 5$ strand cable consisting of four CuNb/Nb_3Sn strands and five stainless steel strands, the stress tolerance of 582 MPa is attained at 0.4% strain.

Fig. 2 shows the schematic cross sectional view of the designed CuNb/Nb_3Sn strand cables. To ensure an operation current of 1000 A for the designed CuNb/Nb_3Sn strand cables, the diameter of a CuNb/Nb_3Sn strand was determined as a function of magnetic field. The operation temperature was selected to be 2.0 K of the superfluid helium condition and it is the temperature of the operation current margin.

Table II gathers the design values of a 20 T-ϕ400 mm room temperature bore (RT-bore) superconducting outsert, employing the CuNb/Nb_3Sn strand cables. A 20 T-ϕ400 mm RT-bore superconducting outsert is composed of 5 layer CuNb/Nb_3Sn coils and two layer NbTi coils. The coil parameters are ϕ = 1,332 mm outer diameter, ϕ = 440 mm inner diameter, and 1,321 mm coil height. Superconducting outsert

TABLE II
DESIGNED PARAMETERS OF A 20 T-ϕ400 mm SUPERCONDUCTING MAGNET FOR A 45 T HYBRID MAGNET

Coil ID	-	L1	L2	L3	L4	L5	L6	L7
Superconductor	-	CuNb/Nb_3Sn+SUS					NbTi+SUS	
Strand diameter	mm	2.17	1.46	1.73	1.18	1.11	1.35	0.99
Cabling structure	-	(6+1)	(8+1)	(3+4)	(4+5)	(4+5)	(3+4)	(3+4)
Conductor diameter with insulation	mm	6.81	5.58	5.49	4.56	4.31	4.35	3.27
Inner diameter	mm	440	570	700	826	966	1098	1216
Outer diameter	mm	560	690	816	956	1088	1206	1332
Coil height	mm	797	998	1180	1278	1319	1319	1321
Number of turns	-	1170	2148	2580	4480	4896	4242	8080
Operating current	A	908	908	908	908	908	908	908
Current density of a conductor	A/mm^2	35.1	51.2	55.2	78.3	88.5	90.6	169
Current density of a coil	A/mm^2	22.1	33.0	34.0	49.2	55.2	54.1	95.6
Magnetic field contribution	T	1.4	2.1	2.1	3.3	3.3	2.8	5.0
Maximum field	T	20.4	19.0	16.9	14.7	11.1	9.10	8.35
Operating temperature	K	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Current sharing temperature	K	4.5	4.5	4.5	4.7	7.4	4.5	4.5
Hoop stress	MPa	158	278	326	477	475	360	396
Compressive stress	MPa	-8	-23	-38	-68	-81	-76	-127

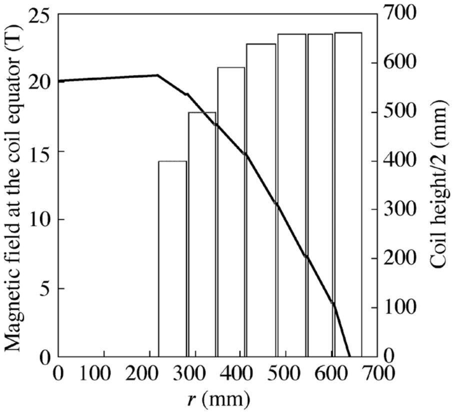

Fig. 3. Magnetic fields generated at the coil equator for a 20 T-ϕ400 mm room temperature bore superconducting outsert. The generated magnetic field is 20 T at the center of the coil. The maximum coil height is 1321 mm at the L7 NbTi layer coil.

is designed to generate 20 T at the operation current of 908 A and at 2.0 K.

This outsert will come across the full excitation current of 1,000 A at 22 T, and the current margin up to 1,000 A will lead to the coil operation stability. The magnetic stored energy is estimated to be 144 MJ at 20 T.

Fig. 3 shows the magnetic field generation at the coil equator. The maximum hoop stress appears in the outer layer CuNb/Nb_3Sn section coils (L4 and L5), and the hoop stress value of around 480 MPa is supposed. The maximum compressive stress is calculated to be 81 MPa for the L5 layer CuNb/Nb_3Sn coil and 127 MPa for the L7 layer NbTi coil. The coil space current density is 22.1 A/mm^2 as low as 62% of the conductor current density for the L1 layer coil. We found that the 20 T-ϕ400 mm RT-bore superconducting outsert can be reasonably designed as compactly as possible.

IV. COIL WINDING TEST BY THE $3+4$ DUMMY STRANDS

As mentioned above, high strength strand cables composed of $6+1$, $8+1$, $3+4$, and $4+5$ strands were designed for the 20 T-ϕ400 mm RT-bore superconducting outsert. The strand cable free spacing was estimated by assuming a model conductor with the same cross section of the circumscribed circle as for each strand cable. To simulate the coil winding process employing for instance $3+4$ strands cable and to examine the effective coil current density considering the strand cable space factor, we prepared $3+4$ dummy strand cables consisting of three copper strands and four stainless steel strands. The dummy strand cable parameters are given in Table III.

TABLE III
PARAMETERS OF THE DUMMY STRAND CABLE USED FOR THE COIL WINDING TEST

Copper strand diameter	0.96 mm
SUS strand diameter	0.99 mm
3+4 strand cable diameter	2.88–2.93 mm
Lapping diameter of Kapton insulator	2.96–3.02 mm
Cabling pitch	62 mm

We much worried about the difference between the space factor estimation and the actual spacing of the strand cable coil. This is because the coil winding process employing strand cables may have a certain deformation of the cross-sectional shape. The $3+4$ dummy strands cable was insulated by 1/3–1/4 lap winding with a 25 μm thick Kapton tape. Considering the relationship between the cable diameter and the inner diameter of the coil, in the design of a 20 T-ϕ400 mm RT-bore superconducting outsert, we will meet the difficulty in winding the L1 section coil with the smallest winding diameter. The L1 section coil is also largely affected by the cable space factor. Therefore, a dummy-coil winding test using the $3+4$ dummy strands cable was given priority.

The dummy coil with ϕ210 mm inner diameter, ϕ263 mm outer diameter, and 46 mm coil height was wound without special problems by employing 111 m long $3+4$ dummy strands cable. Fig. 4 shows the appearance of the dummy coil with 10 layers and 150 turns.

Fig. 4. Dummy coil wound using the $3 + 4$ strand cable and impregnated with epoxy resign.

From the relationship between the measured coil layer diameter and the number of turns, the equivalent diameter of the cable conductor was estimated to be $\phi = 2.90$–2.98 mm. We found that the average difference of -1.6% is obtainable for the equivalent diameter of $3+4$ strand cables. This suggests that the cable conductor space factor is sufficiently well approximated by the cross section of the circumscribed circle for the $3+4$ strand cables.

V. CONCLUSION

We are developing high strength Nb_3Sn strand cables with a large enhancement of the critical current due to the repeated bending treatment for a react-and-wind coil fabrication process, in order to construct a compact and energy-saving 50 T-class hybrid magnet. For this purpose, as a case study, a 20 T-ϕ400 mm room temperature bore superconducting outsert to be integrated into a 45 T hybrid magnet, that has laboratory-easy operation and maintenance and which is composed of five layer Nb_3Sn strand cable coils and two layer NbTi strand cable coils was designed as compactly as possible. The coil parameters of ϕ440 mm inner diameter, ϕ1332 mm outer diameter, 350 H inductance, 144 MJ stored energy, and 908 A operation current in a superfluid helium bath at 2.0 K are shown to be feasible.

We confirmed that the dummy strand cable coil employing the $3 + 4$ strand cables composed of three dummy copper strands and four stainless steel strands can be smoothly wound without any particular problem.

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