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journal or publication title	IEEE Transactions on Magnetics
volume	Vol.30
number	Issue 4 Part 2
page range	pp.1887-1890
year	1994-07-01
URL	http://hdl.handle.net/10655/3891

doi: 10.1109/20.305630

Effect of GFRP Spacer on Local Deformation of Large Superconductor in Coil Pack

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Abstract---Local deformation in a large superconductor caused by GFRP spacers and epoxy adhesives was investigated after compressive rigidity testing. The epoxy adhesive used for attaching the GFRP spacers to the superconductor changed shape from an almost square sheet into a lens-like sheet during deformation, and a dent appeared on the surface of the superconductor. Three-dimensional FEM analysis showed that a compressive stress in the vertical direction of the loading axis existed in the adhesive plane. This stress component makes the adhesive lens-like and it results in the dent created during the compressive testing. This local deformation should yield a part of the permanent deformation observed after the compressive load cycle at 4.2 K.

I. INTRODUCTION

Design and construction of the Large Helical Device (LHD) are in progress at the National Institute for Fusion Science (NIFS) in Japan [1], [2]. The LHD has superconducting poloidal and helical coils, and many efforts have been undertaken to develop these large superconductors [3], [4].

When designing a large superconducting magnet, the mechanical behavior of the wound structure becomes a very important factor since the apparent rigidity affects the design of a coil support structure and the superconducting coil needs to endure the large electro-magnetic force it creates. Also, nonlinear mechanical behavior should yield the instability of the magnet [5]. To research and certify the cryogenic mechanical properties of the superconducting magnet, a cryogenic 10 MN mechanical testing system was installed at the Toki site of NIFS [6], [7], and cryogenic compressive rigidity tests were carried out.

Four coil packs that simulated the helical coil were tested at 4.2 K. All of them showed permanent residual deformation after the first compressive load cycle [8]. The compressive load vs. displacement relationship obtained for the DESIGN-M superconducting coil pack is shown in Fig. 1. Especially on the first load cycle, the displacement did not return to the initial position after unloading, and a residual deformation of about 0.8 mm remained. Also, the apparent rigidity, which is the slope of the load-displacement curve, on loading is quite different from that on unloading. But after the second load cycle, the additional permanent deformation becomes small and the apparent rigidity during both processes is similar.

Three reasons for this residual deformation have been considered. The first one is a mismatch of the contact surfaces between the superconductor and the GFRP spacer. Reference [9] shows that the accuracy of thickness and flatness of the

Fig. 1. Compressive load vs. displacement curves of DESIGN-M coil pack tested at 4.2 K.

GFRP spacer and the superconductor affects the local stress and strain conditions. These local stress and strain conditions cause the global permanent deformation. The second is torsion of the superconductor. As the developed superconductor has twisted strands of NbTi in it, the torsional deformation appears after fabricating. As this deformation depends very strongly on the fabricating process, it is not easy to remove it completely. The last possibility is a local deformation around the contact plane between the superconductor and the GFRP spacer, because an image of the spacer was always observed on the conductor surface after a rigidity test at 4.2 K.

To make the third reason clear, the depression in the conductor surface was investigated, and the stress distribution in the spacer was estimated by three-dimensional FEM analysis. In this report, these experimental and analytical data will be presented, and the relationship between this local deformation and the global permanent deformation will be discussed.

II. LOCAL DEFORMATION OF SUPERCONDUCTOR

Superconductors of 21 kA named DESIGN-M were stacked in a 4 x 4 array. This superconductor has a half-hard copper sheath 2.5 mm thick. To simulate the helical coil, GFRP spacers were placed between each superconductor for electrical insulation. The GFRP spacer shape was 19 mm square and its thickness was 2 mm. The ratio of a GFRP spacer surface area to the total superconductor surface was 0.5. The GFRP spacers were attached to the conductors by epoxy adhesives. As this adhesive has a high viscosity, it is easy to attach the GFRP spacer to the superconductor. The thickness of the adhesive layer was not controlled and not measured during fabrication. The side view of the DESIGN-M coil pack is shown in Fig. 2. Five GFRP spacers were placed on each supercon

Manuscript received September 20, 1993.

ductor surface, and the ends of the coil pack were bundled up by glass tape and epoxy resin.

The sample was set in a special support jig with the longitudinal and transverse directions not constrained. A 20 mm thick stainless steel plate was put on the coil pack, and the prepared coil pack was placed in the cryogenic 10 MN mechanical testing machine as shown in Fig. 3 [6], [7]. The deformation of the coil pack was measured by the displacement gages located at the corner of the support jig. A compressive load of 1500 kN (198 MPa on the GFRP spacer) was applied five times by the hydraulic servo-control system at 4.2 K. After the cryogenic mechanical test, an additional compressive load of 1400 kN (185 MPa on GFRP spacer) was applied at 300 K to make the local deformation clear.

After mechanical testing the test coil pack was disassembled, and the depth of the dent was measured by the surface roughness indicator. The indicator scanned the top surfaces along the center line of the longitudinal direction of each superconductor. Although five GFRP spacers were attached on each surface, only the three dents (the second to the fourth GFRP spacer) located on the center portion of the superconductor were investigated, since the deformation of both ends of each superconductor was extremely large.

An example of the scanning results is presented in Fig. 4. This result shows conductor No.2 of which location is described in Fig. 3. The dent is obviously formed under the GFRP spacers, and its bottom is not flat but round. But edge traces of the GFRP spacer were not clear. Probably the edge of the spacer would not contact the superconductor strongly because of the adhesive layer thickness. As the additional compressive load was rather higher, the top surface of the superconductor also deformed plastically by a mass expansion caused by a deformation restriction of the GFRP spacer. Therefore, in this study, the depth of the dent was defined as the distance from the tangential line which attached the two peaks located on both sides of a certain dent to the bottom of

that dent. So, the depth appearing in this study does not present the actual depth and might include the plastic deformation of the superconductor itself.

The results of the depth measurements are summarized in Table I. Since the strain gages were attached on the region between the second and the third GFRP spacers of conductors No.9 to No.12, the depth scanning could not be carried out there. The depth of the three dents measured on each respective superconductor are similar, showing that the compressive load acted on each GFRP spacer and that the adhesive thickness were almost the same. But one superconductor gave a large dent depth compared with other superconductors in the same layer. This superconductor could have received a larger compressive load during the first load cycle. Once the dents were formed, the applied load would be shared with the other superconductors, and the permanent deformation would not increase extremely after the second load cycle.

The averages of the dent depth on the fourth layer (No.13 to No.16) were smaller than those on the other layers. This means that the compressive load was transformed uniformly to the forth layer, reducing the local deformation.

From these results, the local deformation around the GFRP spacer would produce a part of the global residual deformation observed in the compressive load-displacement relationship.

III. STRESS ANALYSIS IN GFRP SPACER

To investigate the mechanism that created the dent, a deformation aspect and stress condition should be known. So, three-dimensional elastic FEM analysis was carried out to estimate them roughly. The FEM model is shown in Fig. 5. A model of 1/8 of the geometry was prepared because of its symmetry, and consisted of the superconductor and the GFRP spacer. (The adhesive layer was not included.) After testing the coil pack the size of the superconductor was changed [4]. The shape and dimensions are different from the coil pack

Fig. 2. Side view of DESIGN-M coil pack.

Fig. 3. Set-up view of test coil pack and location of displacement gages.

Fig. 4. Result of depression investigation in superconductor surface along the center line. (Conductor No.2)

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TABLE I
SUMMARY OF DEPTH MEASUREMENT OF DENTS

Conductor No.	Measured position			Average (mm)
	2nd spacer (mm)	3rd spacer (mm)	4th spacer (mm)	
1	0.345	0.310	0.375	0.343
2	0.252	0.245	0.345	0.281
3	0.475	0.535	0.438	0.483
4	0.435	0.330	0.360	0.375
5	0.242	0.220	0.205	0.222
6	0.280	0.298	0.285	0.288
7	0.176	0.225	0.210	0.204
8	0.330	0.290	0.355	0.325
9	****	****	0.272	****
10	****	****	0.262	****
11	****	****	0.133	****
12	****	****	0.200	****
13	0.150	0.155	0.162	0.156
14	0.095	0.054	0.110	0.086
15	0.115	0.172	0.168	0.152
16	0.152	0.150	0.124	0.142

****; not measured.

tested, but analytical results of the new design gave the same tendency as the experiments.

The compressive stress of 98 MPa was applied on the top surface of the GFRP spacers, and the side surfaces of the superconductor and the GFRP spacer were not constrained. The elastic moduli of the superconductor and GFRP spacer were assumed to be 88.2 GPa and 4.9 GPa, respectively, and the Poisson's ratio was 0.3 for both materials. Although, both materials are orthotropic, they are assumed to be isotropic to make a discussion easy. The program code used for this FEM analysis was ANSYS version 4.4.

The deformation aspect is shown in Fig. 6. Each line of A to I shows the displacement in the compressive direction. The edge portion of the GFRP deformed clearly not only to the superconductor side but also to the outside, because there was not any restraint on the side surface and the GFRP spacer has a smaller elastic modulus than that of the superconductor. On the other hand, the center of the GFRP spacer stayed almost flat. A displacement aspect inside the GFRP spacer is almost the same as that on the top surface. Therefore, a shear stress

Fig. 5. Model of three-dimensional elastic FEM analysis.

Deformation (mm)
A : -8.49×10^{-2} F : -3.44×10^{-2}
B : -7.48×10^{-2} G : -2.44×10^{-2}
C : -6.45×10^{-2} H : -1.43×10^{-2}
D : -5.46×10^{-2} I : -0.42×10^{-2}
E : -4.45×10^{-2}

Fig. 6. Deformation aspect of GFRP spacer.

will appear around the edge and the side surface. Tresca's equivalent stress distribution in the GFRP spacer is shown in Fig. 7 and Fig. 8. In the center area of the contact plane, the equivalent stress clearly becomes small. In this region, as the GFRP spacer would not deform to the outside in the horizontal direction, another compressive stress appeared in that di

Equivalent stress (MPa)
A : 42.8 E : 99.8
B : 57.1 F : 114.0
C : 71.3 G : 128.3
D : 85.5 H : 142.5

Fig. 7. Equivalent stress distribution in GFRP spacer. (top view)

Equivalent stress (MPa)
A : 42.8 D : 85.5
B : 57.1 E : 99.8
C : 71.3 F : 114.0

Fig. 8. Equivalent stress distribution in GFRP spacer. (bottom view)

Fig. 9. Schematic drawing of deformation of adhesive layer. (Dotted line shows the original position and solid line presents the deformed shape.)

rection. This secondary compressive stress makes the hydrostatic stress component large, and results in a decrease in the equivalent stress. As a matter of course, the hydrostatic stress component reaches a maximum at the center of the contact plane. On the circumference region, the shear stress becomes large with the distance from the center of the contact plane, and the compressive stress in the horizontal direction becomes small. This secondary shear stress increases the equivalent stress. So, on the edge portion, the equivalent stress rises.

From these results, the following mechanism to create the lens-like dents was considered. Fig. 9 illustrates this mechanism. When the GFRP spacer is assumed to not slip, the adhesive near the side surface could deform and expand to the outside, so that the adhesive thickness becomes thin. At the center of the adhesive layer, however, a plastic deformation restraint occurs and its deformation in the horizontal direction is restrained by the secondary compressive stresses. Consequently, the thickness does not change much, and the bottom shape of the dent becomes round.

Following the above consideration, the dent depth and shape will change depending on the constituent materials. Generally speaking, a thinner and softer adhesive layer will reduce the dent depth, and will give a smaller permanent deformation after the compressive load cycle.

IV. SUMMARY

Dents have been observed on superconductors after compressive rigidity testing. Permanent deformation was clearly measured after the first compressive load cycle. In this report, the results of the dent shape investigation were presented, and the stress distribution around the contact surfaces was clarified using three-dimensional FEM analysis. The main reason for the dent formation is the compressive stress component perpendicular to the compressive load axis. If the GFRP spacer does not slip during compression, these secondary stress components deform the adhesive layer to become a lens-like.

The total depth of these dents in the compressive direction would yield the permanent deformation of the coil pack. Therefore, to reduce the permanent deformation of the superconducting magnet after compressive loading, a low viscosity adhesive should be used and the thickness of the adhesive layer should be controlled to become as thin as possible.

ACKNOWLEDGMENT

The authors wish to acknowledge Dr. A. Iiyoshi, Director General of NIFS, and Prof. O. Motojima for their continuous encouragement. Also, we would like to thank the members of LHD design group and Department of Engineering and Technical Service of NIFS for their collaboration in testing, and the related people of Mitsubishi Electric Corporation for their contributions to construct the coil packs.

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