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ORIGINAL PAPER

Mechanical Stability of Superconducting Magnet with Epoxy-Impregnated

Yong Ren · Futang Wang · Zhiyou Chen · Wenge Chen

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Abstract We have developed two epoxy-impregnated superconducting magnets using the NbTi superconductor with a cold bore of 100 mm, which consist of three coils, respectively. The first magnet has a bobbin to support three coils, which exhibits poor performance after several training quenches. The poor performance may be caused by epoxy fracture due to stress concentration results from deformation of the windings during energized. To achieve higher magnetic field using NbTi superconductor alone, we design a second superconducting magnet with three bobbins. The second magnet exhibits higher superconducting properties after several training quenches. This paper presents the magnet design and the test results. The detailed analysis of the superconducting performance difference between the two magnets is also discussed.

Keywords Epoxy-resin impregnated · Superconducting magnet · Training quenches

1 Introduction

Superconducting magnets or superconducting coils with epoxy-impregnated often exhibit significantly training quenches [1–3]. Recently, we observed an abnormal phenomenon in a superconducting magnet with epoxy impregnated, i.e., the total magnetic field generated by all coils in a magnet when all coils were energized simultaneously which is less than the magnetic field generated by a single coil after several training quenches.

The magnet includes two parts, the inner part formed by the inner two coils and the outer part by the outermost coil. The magnet has one bobbin to support these windings. The maximum central field only reached 5.5 T corresponds to an operating current of 65 A after twenty training quenches when two parts of the magnet were energized simultaneously, which is well below the design value. However, the maximum central magnetic field of the inner part of the superconducting magnet reached 5.9 T corresponds to an operating current of 180 A after three training quenches and the outer part reached 6 T at 117 A after ten training quenches when the inner part and the outer part were energized separately.

There are several reasons that cause the abnormal phenomenon. One possible reason is that the inner part and the outer part of the magnet are non-coaxial coils. The deformation of the windings can taken place when energizing the whole magnet. The stress concentration of the windings occurs arise from the windings deformation.

To achieve higher magnetic fields, we design and manufacture a second superconducting magnet so as to generate a central magnetic field up to 9.0 T. The second superconducting magnet has also three coils. Each coil was wound on a separate bobbin. The second magnet generated a central magnetic field of 8.8 T at 142 A after twenty training quenches. In this paper, the design of the magnets, test results, and the detailed analysis of the performance difference between two magnets arepresented.

Y. Ren (✉) · F. Wang · Z. Chen · W. Chen
High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei 230031, China
e-mail: renyong@mail.ustc.edu.cn

Table 1 Design parameters of two superconducting magnets

Coil name		C1	C2	C3
Strand			NbTi	
Strand diameter	mm	0.85	0.70	0.6
Cu/non-Cu		1.3	1.3	1.6
Inner diameter	mm	110.0	136.0	149.0
Outer diameter	mm	136.0	146.0	182.0
Height	mm	244.0	244.0	244.0
Turns		4502	2711	12,070
Operating current	A		65	
Total inductance	H		22.85	
Stored energy	J		48,278	
Central magnetic field	T		5.48	
		C4	C5	C6
Strand			NbTi	
Strand diameter	mm	1.3	0.85	0.6
Cu/non-Cu		3	1.3	1.6
Inner diameter	mm	106.0	157	196
Outer diameter	mm	143.4	180	224.0
Height	mm	244.0	244.0	244.0
Turns		2928	3790	8362
Operating current	A		142	
Total inductance	H		18.25	
Stored energy	J		184,013	
Central magnetic field	T		8.83	

2 Design and Test of the First Superconducting Magnet

2.1 Design and Fabrication of the First Superconducting Magnet

The first magnet consists of three coaxial coils with a cold bore of 100 mm which was wound on a bobbin. Three types of superconducting wires were adopted for the superconducting magnet design. The diameters of these wires are 0.85 mm, 0.7 mm, and 0.6 mm, respectively. The main parameters of the first superconducting magnet are listed in Table 1. Figure 1 shows the short sample characteristics of these superconducting wires. As a result of large mechanical stress in these coils, all coils are epoxy-impregnated. First, the two inner coils were vacuum pressure impregnated and heat-treated as an integral to form the inner part. Next, four layers of stainless steel wires were wound onto the inner part to reinforce the structure. Then the outermost coil was wound onto the reinforcement structure. After that, all coils were also vacuum pressure impregnated to form a solid coil. Finally, stainless steel wires were wound on the solid coil to reinforce the structure.

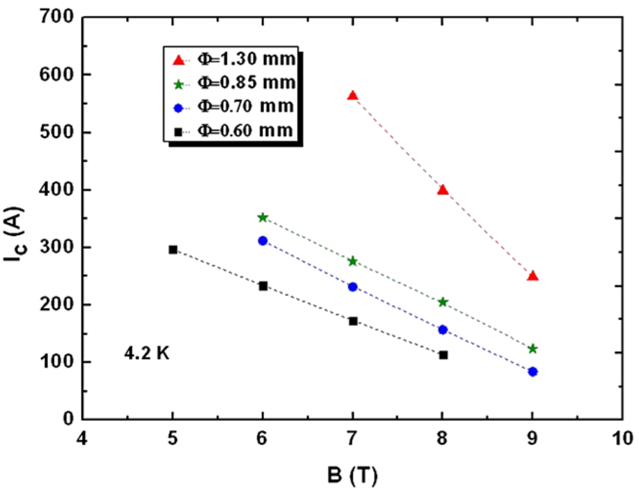


Fig. 1 Critical current values measured at 4.2 K as a function of magnetic field for four NbTi strand samples with different diameters; the different curve symbols are explained in the figure *inset*

2.2 Test Results

At first, a test of the first superconducting magnet using a power supply was performed. The central magnetic field of the magnet is up to 5.5 T at 4.2 K corresponds to an operating current of 65 A after twenty training quenches. The test results show that there is still no room to further improve the performance of the superconducting magnet.

Then we tested the inner part and the outer part, respectively, to see if there is something wrong with these coils due to several training quenches. After three training quenches, the inner part reached 5.9 T at 180 A. The following test results of the outer part shown that it generated a central magnetic field of 6 T at 117 A after ten training quenches. It means that coils of the inner part and of the outer part were not severe damage caused by training quenches. The central magnetic field of the whole magnet, however, does not exceed 5.5 T when two parts were energized simultaneously.

3 Design and Test of the Second Superconducting Magnet

3.1 Design and Fabrication of the Second Superconducting Magnet

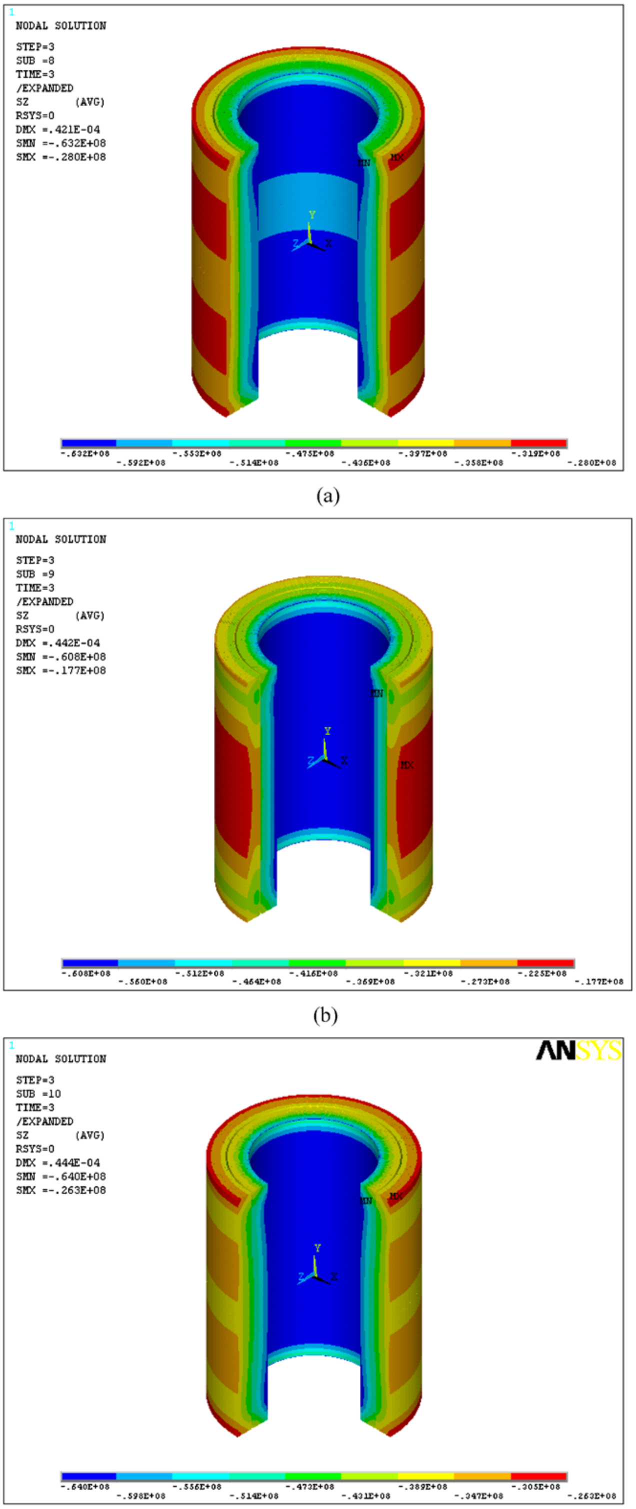
Since the measured results of the first magnet are well below the design value, therefore, we decided to design and manufacture a second magnet. The second magnet also consists of three coils. Each coil was wound on a separate bobbin. The main considerations are as follows. First, it is convenient to protect superconducting coils and to repair some damaged coils in the case of training quenches [4, 5]. Second, three separate bobbins are employed to improve the mechanical stability against the electromagnetic forces during energizing the magnet [5]. Three types of superconducting wires were adopted for the superconducting magnet design. The diameters of these superconducting wires are 1.3 mm, 0.85 mm, and 0.7 mm, respectively. The main parameters of the second magnet are shown in Table 1. All coils are resin-impregnated with epoxy. Besides, stainless steel wires were employed to reinforce the coil structure. All coils are connected in series and can be charged with a single power supply. In addition, two layers of polytetrafluoroethylene (PTFE) were used between stainless steel bobbin and coils so as to against the high voltage during quenches.

3.2 Test Results of the Superconducting Magnet

After twenty training quenches, the central field of the second magnet reached 8.8 T at an operating current of 142 A and 4.2 K.

4 Mechanical Behavior Analysis and Discussion

Mechanical disturbances are common reasons for the persistent occurrence of premature training quenches [6, 7]. As a result of a large performance difference exists between two magnets, it is necessary to evaluate the mechanical behavior of the two magnets. In this study, a 2-D nonlinear model using software ANSYS was used to evaluate the mechanical performance of these magnets. Figure 2 shows the hoop stress of the first superconducting magnet for three conditions. The three conditions are: (a) the central magnetic field of the magnet reached 5.9 T at 180 A during energizing the inner coils, (b) the central magnetic field reached 6.0 T at 117 A during energizing the outermost coils, and (c) the central magnetic field reached 5.5 T at 65 A during energizing all coils. Figure 3 shows the hoop stress of the second superconducting magnet when the central magnetic field reached 8.8 T at 142 A. As shown in Fig. 2, the hoop stress of the first superconducting magnet is well below the allowed value [8]. In addition, the operating current of the first magnet, as shown in Fig. 1, is well below the critical current of short sample when all coils were energized simultaneously. Therefore, we speculated that the large performance difference between the two superconducting magnets may be caused by stress concentration results from coil deformation when energizing the magnet in the case of the two parts of the first superconducting magnet are non-coaxial. If two coils are non-coaxial, a repulsive force in radial direction will be produced as a magnetic interaction [9, 10]. If the radial force exceeds a certain value, the release sufficient heat results from epoxy fracture to cause a quench of a superconducting magnet.



(a)

(b)

(c)

Fig. 2 Hoop stress of the first magnet for three conditions. (**a**) The central magnetic field of the magnet reached 5.9 T during energizing the inner coils with 180 A; (**b**) the central magnetic field reached 6.0 T during energizing the outermost coils with 117 A, and (**c**) the central magnetic field reached 5.5 T during energizing all coils with 65 A

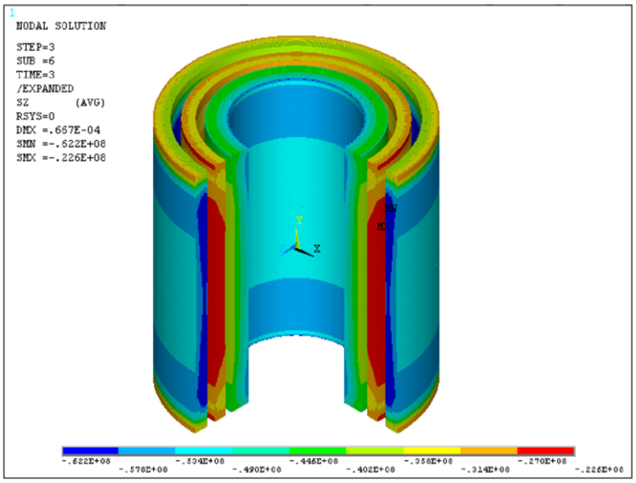


Fig. 3 Hoop stress in the second superconducting magnet when the central magnetic field of the magnet reached 8.8 T at 4.2 K

The radial electromagnetic force between two current carrying coils can be derived from the general expression with their mutual inductance gradient [11]

$$F = \frac{\partial M_{1.2}}{\partial d} I_1 I_2 \tag{1}$$

where I_1 and I_2 are currents of two non-coaxial coils and $M_{1.2}$ is their mutual inductance, d is the generalized coordinate. In this paper, we use the filament method to calculate the mutual inductance between two circular coils of rectangular cross-section with parallel axes [12]. The mutual inductance between two non-coaxial filamentary circular coils with parallel axes can be expressed as [12],

$$M = \frac{\mu_0}{\pi}\sqrt{R_P R_S}\int_0^{\pi} \frac{(1 - \frac{d}{R_S}\cos\vartheta)}{\sqrt{v^3}} d\vartheta \tag{2}$$

where

$$\alpha = \frac{R_S}{R_P}, \qquad \beta = \frac{c}{R_P}, \qquad k^2 = \frac{4\alpha v}{(1+\alpha v)^2 + \beta^2}$$

$$v = \sqrt{1 + \frac{d^2}{R_S^2} - 2\frac{d}{R_S}\cos\vartheta}$$

$$\Phi(k) = \left(\frac{2}{k} - k\right)K(k) - \frac{2}{k}E(k)$$

$K(k)$: complete elliptic integral of the first kind; $E(k)$: complete elliptic integral of the second kind; R_P: radius of the primary coil; R_S: radius of the secondary coil; c: distance between planes of coils; d: distance between axes.

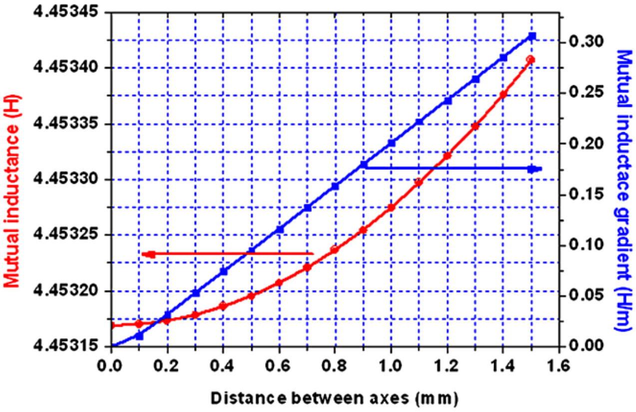


Fig. 4 Mutual inductance and mutual inductance gradient as a function of distance between axes of coils

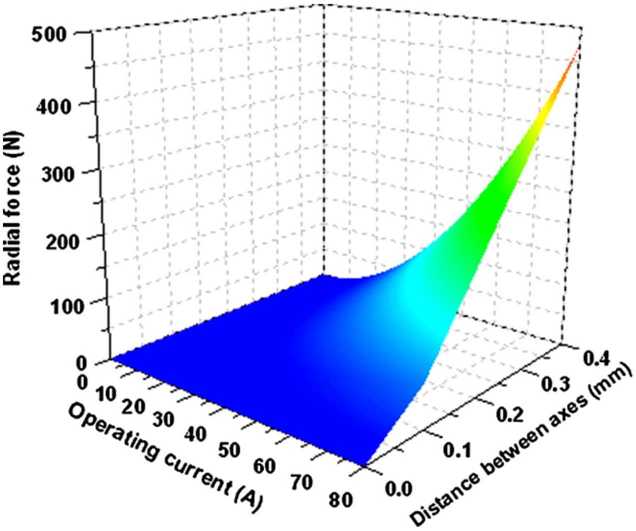


Fig. 5 Radial force as a function of distance between axes of coils for different operating current

Figure 4 shows the mutual inductance and its gradient as a function of distance between axes of coils. Figure 5 shows the radial electromagnetic force as a function of distance between axes of coils and of the operating current. As shown in (1) and Fig. 5, the radial magnetic force is proportional to the square of the operating current of the coils. The coil deformation and stress concentration is likely to occur due to the asymmetric distribution of the radial electromagnetic force results from an unsatisfactory impregnation and winding. Initially, the stress energy is small as the level of the coil deformation and stress concentration. But once the stress exceed a certain value at one location in the winding, stress induced cracking of the epoxy is likely to occur. In addition, the coil deformation and wire motion is unlikely to the behavior of a single wire but the whole coil as an integer. Under this condition, one can expect that a quench will be initiated if the released stress energy exceeds minimum quench energy [13, 14]. In fact, only a small amount of disturbance energy, in the range of micro joules, is needed to trigger a quench for an adiabatic magnet [10]. As a result of the increases in electromagnetic force with increasing operating current, considerable stress energy release of the magnet will occur due to the asymmetric distribution of the radial electromagnetic force. The inner coil and the outermost coil, however, exhibit a better performance when they were charged separately due to the absence of large asymmetric radial electromagnetic force comparison with the circumstance when the two parts were charged simultaneously.

For the second superconducting magnet in which each coil has one bobbin, as shown in Fig. 3, the hoop stress of the second superconducting magnet can be comparable to that of the first superconducting magnet. As a result of a good bobbin support, a large asymmetric radial electromagnetic force between windings can be relieved when they were charged with a power supply. The second superconducting magnet exhibits a better superconducting performance. The second magnet reached 8.8 T at 142 A and 4.2 K.

5 Conclusion

We have developed two superconducting magnets using NbTi superconductors. The two magnets exhibit a striking difference in superconducting performance. The first superconducting magnet only reached 5.5 T of central field corresponding to an operating current of 65 A when all coils are charged simultaneously. The second magnet reached 8.8 T of central field at 142 A. The detailed finite element analysis of hoop stress and the calculation of the radial force between coils are performed to predict the mechanical behavior of the two magnets. We speculated that the asymmetry distribution of the radial force between coils is the main reason for premature quench for the first superconducting magnet. Test results show that each coil has one bobbin which can improve the magnet stability.

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