Close circuit test of MgB$_2$ coil with superconducting joints and a persistent current switch

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Abstract. Close circuits made of Fe and composite sheathed, mono- and multi-filament MgB$_2$ wires were fabricated and tested in liquid He and conduction cooling environments for the demonstration of persistent current operation in such as the magnetic resonance imaging (MRI) magnets. Persistent current switches and superconducting joints were designed and installed in the circuits. The decay time of the captured magnetic field in the coil and joint resistance were measured. According to the results, the resistance of the closed circuit at low temperature can be less than $10^{-13}$ Ω, showing a potential for application in the currently develop MgB$_2$ MRI systems. The causes of the circuit resistance were also discussed.

1. Introduction

As long MgB$_2$ wires and tapes became commercially available [1-7], the large scale applications of MgB$_2$, such as the magnetic resonance imaging (MRI) magnets were taking more and more interests of the world wide researchers [8-16]. Manufactured via powder in the tube (PIT) method, the piece length of the commercialized MgB$_2$ wires were commonly from 100 m to several kilometers with the critical current density of better higher than $10^4$ A/cm$^2$, at 4.2 K, self field, and better higher than $10^4$ A/cm$^2$ at 20 K, self field [3, 4, 10]. However, it is necessary to connect pieces of wires to meet the needs of the large scale applications. Soldering, cold pressure welding and diffusion welding could only create resistive joints, which causing extra heating and unexpected quenching. It was also the main cause of the time decay of the working current and thus the field generated by the magnet, especially in the persistent current (PC) operating mode, which is preferred in MRI and many other magnets. Hence, superconducting joints were literally required for the PC operation. Moreover, working in the PC mode also means less power consumption and better cooling conditions compared to the magnets driven by continuous external magnetization power sources. This was important to the conduction cooling magnets, where the tolerance of over heating was strictly limited. Supported by a project aiming to the development of full-body MRI system using MgB$_2$ wires, researches considering the superconducting jointing and PC operation switches utilizing PIT fabricated MgB$_2$ wires and tapes were proposed. In this work, encouraged by the early attempts of the superconducting jointing in
MgB$_2$ wires [4, 17, 18], a jointing technique suitable for building close circuit coils was developed according to the chemical and physical properties of Mg, B and MgB$_2$ at the pressure, temperature and ambient at the jointing area [19]. Close circuits were then made using Fe and composite sheathed MgB$_2$ wires and tapes and tested in both liquid He and conduction cooling environments. The test results demonstrate a potential of PC operating in the future large scale MgB$_2$ magnets.

2. Experimental details

The jointing technique proposed here was in analogy to the PIT method in manufacturing the MgB$_2$ wires, where Mg and B powders were mixed and compressed in the metal sheath, then heated to about 973 K for heat treatment. Figure 1 illustrated the sketch for one of the jointing process. The joint area was compressed at room temperature in air, and then sintered in a furnace, as shown in figure 1d).

![Figure 1 Sketch of the jointing process of wires](image)

For tapes with rectangular cross sections, the jointing method was the same as reported in the previous work [19]. The sheath material, cross section, superconductor core size and number of filaments of the four types of samples used in this work, named A to D, were listed in table 1. In the same table, the parameters of a special type of sample E, used as the sheath material sample type D were also listed.

| Sample | Sheath material | Cross section (mm$^2$) | Filling factor | Core type | Filaments |
|--------|----------------|------------------------|---------------|-----------|-----------|
| A      | Fe             | 3.5 x 0.4              | 40 %          | reacted   | 1         |
| B      | Fe             | 3.5 x 0.4              | 40 %          | raw       | 1         |
| C      | Ni/Fe/Cu       | 3.65 x 0.65            | ~0.21         | reacted   | 14        |
| D      | Fe/Cu          | φ 0.8                  | 25 %          | raw       | 1         |
| E      | Fe/Cu          | φ 1.6                  | 25 %          | raw       | 1         |

Single-turn coils were firstly fabricated with direct connections along the circumference. Because the inductance was small, the field decaying processes of the single-turn samples were not possible to be recorded measure after if excitation by energizing. Thus, they were installed in a test device illustrated in figure 2, with a magnetization coil on the outer side of the framework and a heater for switching.
As it was difficult to control the banding radius and the strains while jointing and processing, and the captured fields of the single-turn coils were small, multi-turn coils were fabricated and the joints were separately made utilizing short straight pieces of sample type E. This avoided the bending strains at the joint areas, and as the inductance of the multi-turn coil was much larger than that of the single-turn ones, which enabled the external power source excitation tests. The sketch of the multi-turn coil close circuit installed in the testing device with an external power source was illustrated in figure 3.

Several test coils were fabricated using various types of tapes and wires, the parameters of the coils and the descriptions of the joints were listed in table 2.

Table 2. The parameters of the test coils and the joints
In both testing device shown in figure 2 and 3, a precise Hall probe was installed at the center of the coil to monitor the field.

For the external field magnetization routine, the continuous current was firstly applied to magnetization coil. This current which generated a magnetic field in the testing device bore and hence supplied an external background filed to the sample coil. After the device was cooled down to the designed temperature, monitored by an Rh-Fe resistance thermometer installed close to the sample coil, the magnetization current was slowly turned down to zero and a faradic current was then generated in the sample. If the joint in the sample coil was superconducting, i.e., the circuit resistance \( R_L \) was very small, the faradic current would be decaying very slowly. The magnetic field at the center of the sample coil was continuously monitored by the precise Hall probe, thus, in principle, the time decay characteristic of the field and the faradic current in the sample coil could be measured. After that, the resistance of the circuit was calculated by the decay time constant \( \tau \) and the inductance of the sample coil \( L \) according to the follow equations:

\[
L \frac{dl}{dt} + R_L \cdot I = 0
\]

\[\tau = \frac{L}{R_j}\]

Here, \( I \) was the time dependent current in the sample coil, \( t \) was the time, \( R_j \) was the joint resistance, which tentatively replaced \( R_L \) as the rest part of the coil was superconducting at the experimental temperatures.

For the tests with external power source, the sample coil was connected both to the switch and the power source by two joints, while a special designed switch using MgB\(_2\) wire E was inserted in between, as illustrated in figure 3. The switch was controlled by a heater and its temperature was monitored by a Pt resistance thermometer. During the experiment, the heater was firstly applied a continuous current, so the switch and the joints were heated up to a temperature above the \( T_c \) of MgB\(_2\). When the coil was cooled down to the designed temperature, monitored by an Rh-Fe resistance thermometer installed in its bore and close to the inner side of the Al\(_2\)O\(_3\) framework, the magnetization current was applied to the coil from the current leads. The current was then shared by the parallel connection among the coil, the switch and joints according to the following equations:

\[
I_0 = I_1 + I_2,
\]

\[
V_0 = V_1 = V_2 = I_1[R_j + R_s(T)] = L \frac{dl}{dt} + I_2 R_s(I_2)
\]

Here, \( I_0 \) was the current supplied by the power source, which was monitored by an amperometer attached directly to the out lead of the source. \( I_1 \) and \( I_2 \) were the current shared in the switch branch and the coil, respectively. \( R_s \) was the resistance of the switch, which was variable according to the temperature \( T \), while \( R_s(I_2) \) could be estimated according to the \( V-I \) characteristics of the coil. At the magnetization process, the voltage across the coil was continuously monitored. It was obvious that when the sweep speed of the magnetization current \( I_0 \) was turned down, the share of the current in the coil \( I_2 \) would increase due to the decline of the reactance, and shortly after the magnetization current became stable, the magnetic field at the center of the coil, monitored by a precise Hall probe would...
become stable, too. After that, the heating current was slowly turned down, the switch and joints were allowed to cool down and became superconducting stage, and then, at this stage, the sample coil became a superconducting close circuit. Finally, the magnetization current was also slowly turned down to zero. The magnetic field at the center of the sample coil was continuously recorded during the experiment to measure the time decay curve of the captured field in the coil.

3. Results and discussions

Typical time decay curve of the captured magnetic field in the single-turn test coil measured in liquid He was shown in figure 4. It was obvious that the capture field was comparatively small and decaying fast. Nevertheless, since the inductance $L$ of the coil was also very small, the calculated resistance of the coil $R_L$, which was tentatively assigned to the joint resistance $R_j$ was less than $10^{-13} \, \Omega$. The liquid He test results of the three single-turn sample coils, coil 1 to 3, were listed in Table 3.

![Figure 4. The time decay characteristics of the field in sample coil 2 measured at 4.2 K.](image)

Table 3. Test results of the sample coils measured at 4.2 K in liquid He

| Coil | $L$ (μH) | $\tau$ (s$^{-1}$) @ 4.2 K | $R_L$ (Ω) @ 4.2 K | $\tau$ (s$^{-1}$) @ 19 K | $R_L$ (Ω) @ 19 K | $B_0$ (mT) |
|------|---------|--------------------------|-------------------|--------------------------|------------------|------------|
| 1    | 4.3 x 10$^2$ | 9.6 x 10$^5$ | 4.13 x 10$^{-11}$ | 5.5 x 10$^4$ | 7.82 x 10$^{-11}$ | 0.40 |
| 2    | 4.1 x 10$^2$ | 7.4 x 10$^5$ | 3.03 x 10$^{-13}$ | 4.98 x 10$^5$ | 8.23 x 10$^{-12}$ | 0.096 |
| 3    | 8.0 x 10$^2$ | 7.8 x 10$^4$ | 6.24 x 10$^{-11}$ | - | - | 4.8 |
| 4    | 387.5   | - | - | - | - | 235 |
| 5    | 85.2    | 4.5 x 10$^7$ | 3.86 x 10$^{-11}$ | - | - | 65.8 |

The conduction cooling measurement was made at 19 K (±0.3K), only coils 1 and 2 were measured at this temperature. The time decay curve of the field in the coils at 19 K was in principle similar to that measured at 4.2 K, while as the joint resistance $R_j$ was much larger compared to that at 4.2 K, the decay time constant $\tau$ was also increased significantly. The results of the estimated $R_j$ and $\tau$ at 19 K were also listed in Table 3.

The multi-turn test coil was fabricated using a “wind and reaction” method, i.e. it was firstly wound and joint using the “raw” wires as reported in the previous work [19], then put into the furnace and heat treated. To qualify the winding and processing conditions, an open circuit, i.e. normal sample
coil, denoted as coil 4, was firstly fabricated and tested in liquid He. In figure 5 the $B$, $V$-$I$ characteristics at the magnetization of coil 4 were shown, respectively. It was clear that the wire was able to carry a working current of about 100 A at 4.2 K, which generated a magnetic field $B_0$ of about 235 mT at the center. From the result, the feasibility of the “wind and reaction” process used in this work was demonstrated.

![Figure 5. The magnetization process of coil 4 measured at 4.2 K, dashed line denoted the magnetic field at the center $B_0$, while the solid line denoted the electrical field $E$ (V divided by the length of the wire used in the coil) across the sample coil.](image)

After that, the closed circuit, coil 5 was fabricated and processed. The switch was prepared with the coil and the joints in the same process, whose resistance was about 0.02 $\Omega$ at 40 K. As the inductance of the coil $L$ was only 85.2 $\mu$H, it was able switch on and off the close circuit effectively at 50 A working current and current sweep rate $dI/dt$ of about 1 A/s. For larger magnets, such as the test coil reported in a 1.5 T magnet, whose $L$ was about 0.17 H [16], the required switch resistance at $dI/dt$ of about 1 A/s would be larger than 0.1 $\Omega$. As the normal state resistivity of the typical commercialized MgB$_2$ tape [4] was as small as 0.03 $\Omega$/m, special designed and fabricated wires were required to build the PC switches for the large scale applications, which might involve utilizing high resistivity sheath materials.

During the measurement, the coil was immersed in liquid He, while the temperature of the switch and the joints was controlled by the heater and thermometer installed closed to the switch. Firstly, the coil was magnetized by the external power source with the switch open. As shown in figure 6 the magnetization process of the coil was tentatively divided into four stages. In the first stage, the heater was on and the excitation current was sweeping up. Short pauses during sweeping demonstrated the current sharing between the coil, which could generate magnetic field at the center and the switch. In the second stage, the magnetization current became stable, and the field became stable with a short delay. In the third stage, the heater was off and the field remained stable. In the final stage, the magnetization current swept down, and the field swept down with a certain delay. As pointed out in the figure with vertical dashed lines, it was possible to observe quick and then slow decay processes of the field, which indicated the variation of the flux flow processes in the superconductor. Nevertheless, at the forth stage, while the magnetization current turned down to zero, the field at the center of the
The magnetization current turned down to zero was recorded as the starting time $t_0$ of the time decay curve of the captured field, as denoted in figure 6 by a vertical arrow.

Figure 6. The magnetization process of coil 5 measured at 4.2 K, the dashed line denoted the applied magnetization current and the solid line denoted the field at the center, while the dashed vertical lines were denotations for the four stages of the operation and the vertical arrow denoted the starting point of the time decay curve.

Figure 7 shows the time decay curve of the magnetic field at the center of coil 5 in the following hour. By fitting the slow decay part of the curve according to equations 1 and 2, the decay time constant $\tau$ in coil 5 was estimated to be about $4.5 \times 10^{-7}$ s$^{-1}$, as listed in table 3. From this result, the estimated resistance of this close circuit sample coil was about $3.86 \times 10^{-11}$ Ω. Compared to the typical circuit resistance of the PC operating devices, which could be less than $10^{-13} - 10^{-14}$ Ω, the resistance of this sample was still large. A possible reason of this resistance was the comparatively low density of the superconductor core in the joint area. Although tightly wrapped by the sheath wire, denoted as sample type E, and compressed with about 0.6 GPa pressure to densify the core in the joint area, microstructure observation demonstrated that the density of the superconductor core at the joint was still not satisfying, pores and cracks were quite often to occur in this area and create weak links in the superconductor. Better matching of the diameters of the basic and the sheath wires could partially solve this problem, while other approaches might include enlarging the joint area and mechanically reinforcing the joint. The “ex-situ” attempts that utilizing Mg, B and MgB$_2$ mixtures in the place of “pure” Mg and B in the wire and the joint area were also scheduled in the future works.

4. Conclusion
In total, the attempt of building and operating closed circuits using MgB$_2$ wires and tapes with PC switches and superconducting joints demonstrated the possibility of the PC usage utilizing only MgB$_2$ wires and tapes, and at about 20 K in the conduction cooling conditions. However, as often seen in the preparing and heat treatment of high critical current “in-situ” MgB$_2$ wires, the density of the superconductor core and the cracks could be a significant drawback for the practical application of the proposed jointing and coil winding methods. It was obvious there were still a lot of efforts to make including material researches and improving the technology of magnet winding. Nevertheless, the
potential of PC operating in MgB₂ magnets, especially at conduction cooling conditions was in great
favour of the wide and cheap applications of the superconducting devices, such as the MRI systems, in
the near future.

![Figure 7. The time decay curve measured in coil 5 at 4.2 K.](image)

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