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Superconductivity for HTS GdBCO CC with heat treatment

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Abstract

The magnetic properties of heat treated O-series high temperature superconducting (HTS) GdBCO coated conductor (CC) tapes which were formed of Ag/GdBCO/Buffer-layers/Stainless Steel (SS), were investigated by employing a Quantum Design PPMS-14. Using a modified Bean model, the critical current density J_c values have been estimated from the $\Delta m_{irr}(H)$ data, which are obtained by measuring the magnetic moment $m(H)$ loops. For a range of intermediate fields, which are interacting or collective flux pinning area, the magnetic flux behaviors were investigated from the relationship $J_c \propto H^{-\beta}$. In addition, the changes of irreversibility magnetic field H_{irr} line of heat-treated O-series HTS GdBCO CC tapes were analyzed, according as the annealing temperature under oxygen flowing increases. Both weak and strong break-downs were found by examining the changes of irreversibility magnetic field H_{irr} lines.

Keywords: HTS GdBCO CC, heat-treatment, critical current density, irreversibility magnetic moment, irreversibility magnetic field

1. INTRODUCTION

It has been more than a decade since the high temperature superconducting (HTS) ReBCO coated conductor (CC) tapes with good superconductivity were commercialized and marketed [1-3]. The development of superconducting application devices such as magnets, cables, and motors, using HTS ReBCO CC tapes, however, is still not reaching the commercial stage. One of the important reasons for their practical application shortage is the inability to manufacture tens of kilometers of long length HTS ReBCO CC tapes. The joining technique between two HTS ReBCO CC tapes without any superconductivity loss, to obtain the long enough length CC tapes, has been actively conducted in many research groups [4-8]. There are three ways to join between HTS CC tapes: superconducting joints, non-superconducting joints of both soldered lap joints and diffusion joints. The methods of both soldered lap joints and diffusion joints may not affect the superconductivity of HTS CC tapes because those joints are performed at below temperatures ~ 400°C, but the superconducting joints can affects the superconducting characteristics by heat treatment at high temperatures [4, 9]. In general, while the superconducting joints are performed, the HTS ReBCO CC tapes are exposed to oxygen heat treatments at high temperatures. The HTS YBCO superconductor with a superconducting transition at ~ 93 K as a single phase has an orthorhombic superconductive phase [10]. During heat treatments, the oxygen balance in the superconductor can be changed and its superconductivity can be lost. Below about 550°C under oxygen annealing the HTS YBCO superconductor is the orthorhombic phase and at higher temperatures changes to a tetragonal phase [10, 11]. So, superconductivity studies are needed according to oxygen heat treatment temperatures for HTS CC tapes.

In this work, the superconducting properties of commercialized HTS GdBCO CC tapes were investigated according to the heat treatment conditions with oxygen atmosphere. The HTS GdBCO CC tapes, which are silver (Ag) protected RCE-DR GdBCO CC with Stainless Steel (SS) substrate, were purchased from SuNam Co., Ltd. The magnetic properties of the heat-treated O-series HTS GdBCO CC tapes were investigated by using PPMS (Physical Property Measurement System). The irreversibility magnetic moment Δm_{irr} was obtained by measuring the magnetic moment $m(H)$ loops. The critical current density J_c values have been estimated from the $\Delta m_{irr}(H)$ data, using the modified Bean critical state model [12-14], as well. The changes of irreversibility magnetic field H_{irr} line of heat-treated O-series GdBCO CC tapes were investigated, according as the annealing temperature under oxygen flowing increases.

2. EXPERIMENTAL APSPECTS

The HTS GdBCO CC tapes were purchased from SuNam Co., Ltd. The composition of HTS GdBCO CC tapes, which were formed of Ag protective layer with SS substrate, is Ag/GdBCO/Buffer-layers/SS. The HTS GdBCO superconducting film with ~ 1.5 μm thick was deposited on an IBAD template by RCE-DR process. A detailed description of the fabrication process is presented elsewhere [1]. After cutting the HTS GdBCO CC tapes with ~ 10 cm length, the heat-treated O-series HTS GdBCO CC specimens were prepared by annealing with oxygen flowing ~ 0.7 litter/min.

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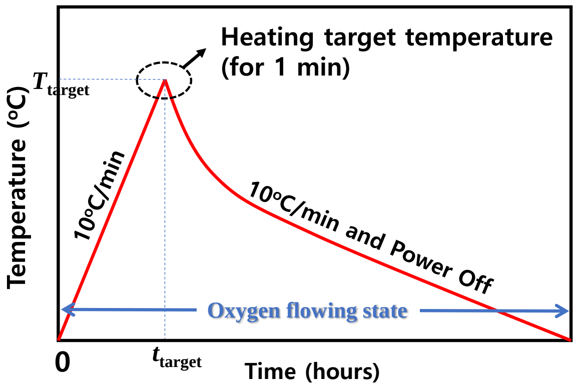

Fig. 1. Heat temperature cycles for the heat-treatment O-series of HTS GdBCO CC tapes.

As shown in Fig. 1, the heat-treatments were carried out by keeping the specimen in oxygen flowing environment for 1 minute at target temperatures – 400°C, 500°C, 600°C, 650°C, 700°C, 750°C, 800°C, 850°C, 875°C, 900°C, 925°C, 935°C, 950°C, and 975°C. The heat-treated O-series HTS GdBCO CC specimens were used to investigate the effect of heat-treatments on the superconducting properties of the HTS GdBCO CC tapes.

The magnetic properties for both origin and heat-treated O-series of HTS GdBCO CC specimens were measured using commercial Quantum Design PPMS-14 instrument. The isothermal magnetic moment $m(H)$ for both origin and heat-treated O-series of HTS GdBCO CC specimens, at temperatures – 20 K, 30 K, 40 K, 50 K, 60 K, 70 K, 77 K and 100 K in fields up to 12 T, were measured. The irreversibility magnetic moment Δm_{irr} was obtained by measuring the magnetic moment $m(H)$ loops. The critical current density J_c values have been estimated from the $\Delta m_{irr}(H)$ data, using the modified Bean critical state model [12-14]. In addition, the irreversibility magnetic field H_{irr} values were obtained from the field at which irreversibility magnetic moment $\Delta m_{irr} \sim 0$ [15-18].

This paper discusses two break-downs in irreversibility magnetic field H_{irr} lines for heat-treated O-series HTS GdBCO CC tapes according as the annealing temperature under oxygen flowing increases. The weak and strong break-downs were found by examining the change of irreversibility magnetic field H_{irr} lines of O-series specimens according to annealing temperatures.

3. RESULTS AND DISCUSSIONS

To investigate the superconducting transition temperature T_c for both origin and heat-treated O-series of HTS GdBCO CC tapes, the diamagnetic properties, the $m(T)$ curves, were measured under zero-field cooled (ZFC) condition in an applied field H = 200 G. All $T_{c,\ onset}$ values, which were determined by the onset temperatures in ZFC $m(T)$, of both origin and heat-treated O-series specimens up to 925°C annealing temperature, are ~ 93.0 K. Fig. 2 shows the superconducting transition temperature T_c versus annealing temperatures T for both origin and heat-treated O-series of HTS GdBCO CC specimens. As shown in Fig. 2, no degradation of the superconductivity of heat-treated O-series specimens, up to 925°C annealing temperature, was observed. Above 935°C annealing temperatures the superconductivity of HTS GdBCO CC specimens, however, were almost lost. These results are consistent with the reference in which HTS YBCO material decomposes at temperatures near 950°C [10].

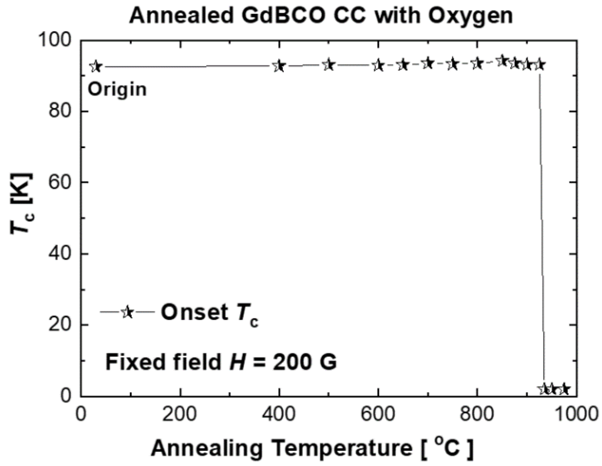

Fig. 2. The superconducting transition temperature T_c versus annealing temperatures T for both origin and heat-treated O-series of HTS GdBCO CC specimens. The T_c values for all specimens were estimated from $m(T)$ curves, which were measured under Zero-field-cooled (ZFC) condition in an applied field H = 200 G.

The superconductive magnetic properties of both origin and heat-treated O-series, which are annealed under oxygen flowing, HTS GdBCO CC tapes were investigated by using a commercial Quantum Design PPMS-14 instrument. Fig. 3-(a) shows the magnetic moment m versus magnetic field H for both origin and heat-treated O-series of HTS GdBCO CC tapes at temperature T = 20 K for H parallel to the c-axis. The measured magnetic moments $m(H)$ were corrected for the background $m(H)$, which was measured at temperatures above T_c.

As mentioned before, the irreversibility magnetic moment Δm_{irr} was obtained by measuring the magnetic moment $m(H)$, like Fig. 3-(a). The $\Delta m_{irr} = [m(H_{dec}) - m(H_{inc})]$ is the difference of magnetic moment m between the increasing field H_{inc} and the decreasing field H_{dec} branches from magnetic moment $m(H)$ loops [15-17]. The critical current density J_c values were estimated from the $\Delta m_{irr}(H)$ data by using the modified Bean critical state model [12-14], $J_c = (20\Delta m_{irr})/((a(1-(a/3b)))V)$, where a and b are the superconductor sample dimensions and V is the superconductor volume.

Both origin and heat-treated O-series of HTS GdBCO CC specimens used in the magnetic property measurements, which have ~ 1.5 μm thick HTS GdBCO film deposited on an IBAD template by RCE-DR process, have dimensions ~ 4 mm by ~ 4 mm. Fig. 3-(b) shows the logarithmic plots of the critical current density J_c versus magnetic field H for both origin and heat-treated O-series of HTS GdBCO CC tapes at temperature T = 20 K for H parallel to the c-axis. As shown in Fig. 3-(b), the J_c values of 500°C heat-treated

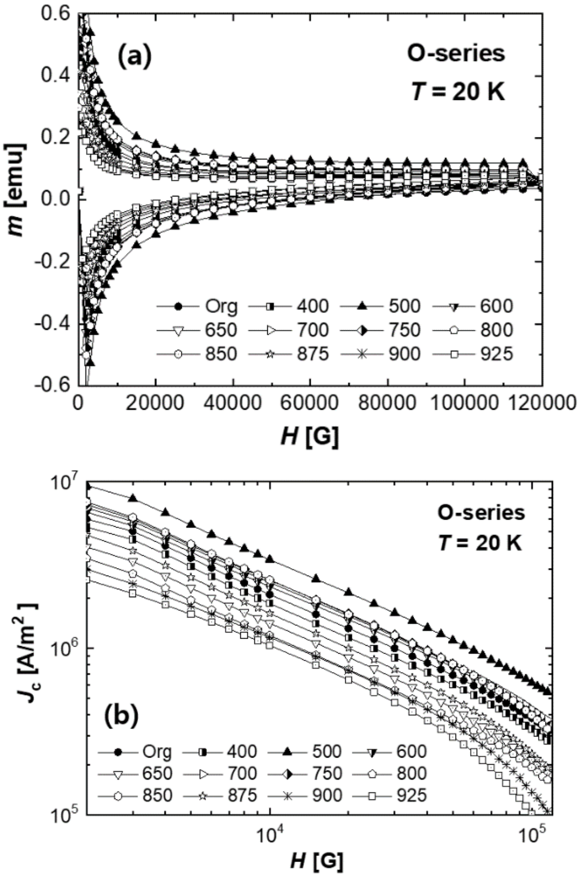

Fig. 3. (a) The magnetic moment m versus magnetic field H and (b) the logarithmic plots of the critical current density J_c versus magnetic field H, for both origin and heat-treated O-series of HTS GdBCO CC tapes at temperature T = 20 K for H parallel to the c-axis.

HTS GdBCO CC specimen are much higher than those of the origin HTS GdBCO CC specimen. In addition, the J_c values of several heat-treated HTS GdBCO CC specimens are a bit higher than those of the origin HTS GdBCO CC specimen, too. These results are attributed to the point defects caused by the coming out of oxygen in the specimens.

Fig. 4-(a) shows the semi-logarithmic plots of the critical current density J_c versus annealing temperatures T for both origin and heat-treated O-series of HTS GdBCO CC specimens at temperature T = 20 K and H = 1 T for H parallel to the c-axis. The inset shows the magnified plots near J_c values of both origin and heat-treated O-series of HTS GdBCO CC specimens. As mentioned in Fig. 3-(b), the J_c values of both 500°C and some heat-treated HTS GdBCO CC specimens are a bit better than those of the origin HTS GdBCO CC specimen. These results can be understood as a magnetic flux pinning effect, which can be caused by point defects due to oxygen deficiency through heat treatments. The magnetic flux pinning effect can be confirmed from the logarithmic plots of the critical current density J_c versus magnetic field H as shown in Fig. 3-(b).

As presented in previous papers [15-17], from the log(H) relation graph for log(J_c) of both origin and heat-treated O-series of HTS GdBCO CC specimens as

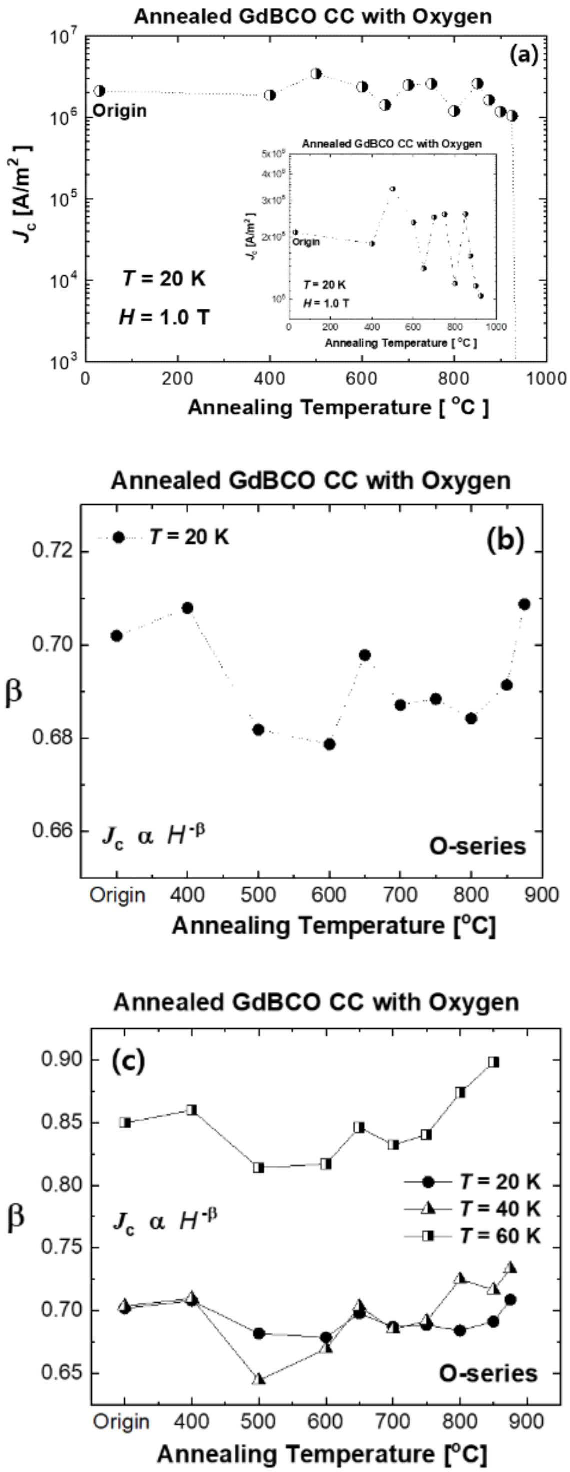

Fig. 4. (a) The semi-logarithmic plots of the critical current density J_c versus annealing temperature T for both origin and heat-treated O-series of HTS GdBCO CC specimens at temperature T = 20 K and H = 1 T for H parallel to the c-axis. The inset shows the magnified plots near J_c values of both origin and heat-treated O-series of HTS GdBCO CC specimens. (b) The plots of β versus annealing temperatures T, at temperature T = 20 K with external fields H parallel to the c-axis. (c) The plots of β versus annealing temperatures T at temperature T = 20 K, 40 K, and 60 K, respectively, with external fields H parallel to the c-axis.

shown in Fig. 3-(b), physical properties such as magnetic flux pinning effect can be explained by the relational expression of critical current density J_c and magnetic field H related to the behavior of magnetic fluxes according to the magnetic field intensity, the relational expression of $J_c \propto H^{-\beta}$ [18]. Here β values are the physical indicative quantity indicating the magnetic flux pinning effect. Analytically, they can be divided into three areas: firstly, individual or independent flux pinning area with $\beta \approx 0$, secondly, interacting or collective flux pinning area with $\beta \approx 0.6 \sim 1.2$ of linearly decreasing part, and thirdly, freely flux moving area with $\beta \gg 2$ [16].

The β values of interacting or collective flux pinning area were obtained from the linearly decreasing parts of the Fig. 3-(b). Fig. 4-(b) and -(c) shows the plots of β versus annealing temperatures T, (b) at temperature T = 20 K and (c) T = 20 K, 40 K, and 60 K, respectively, with external fields H parallel to the c-axis. The lower β values show the better magnetic flux pinning effect. As shown in Fig. 4-(b) and -(c), the β values of 500 ~ 600°C heat-treated HTS GdBCO CC specimens are a bit lower than that of the origin HTS GdBCO CC specimen. These results are consistent with those results as shown in Fig. 4-(a).

In general, the irreversibility magnetic field H_{irr} lines is one of important superconductive aspects in practical applications of HTS CC tapes, such as superconducting power systems and magnets. As mentioned before, the irreversibility magnetic moments Δm_{irr} (= $m(H_{dec})$ - $m(H_{inc})$), which are the difference of magnetic moment m between the increasing field H_{inc} and the decreasing field H_{dec} branches from $m(H)$ magnetic moment loops, can be obtained from Fig. 3-(a). The H_{irr} values were estimated from the field at which the Δm_{irr} goes to zero.

Fig. 5 shows the irreversibility magnetic field H_{irr} versus annealing temperatures T for both origin and heat-treated O-series of HTS GdBCO CC specimens at temperature T = 40 K, 50 K, 60 K, and 77 K, respectively, for H parallel to the c-axis. As shown in Fig. 5, the H_{irr} values linearly decrease as the annealing temperatures T increase. In addition, there are two break-downs, such as weak break-down and strong break-down, in the change of the H_{irr} values according to increasing the annealing temperatures. The strong break-down occurs at a heat treatment of above 935°C, which means loss of superconducting properties. The strong break-down, that is superconducting phase transition, is consistent with the result of Fig. 2.

The decreasing rates (dH_{irr} / dT) of the H_{irr} values according to increasing the annealing temperatures T are -40.98 G/°C at T = 40 K, -60.00 and -204.07 G/°C at 50 K, -30.26 and -120.68 G/°C at 60 K, and -11.19 and -56.95 G/°C at 77 K. Interestingly, a weak break-down can be found in the Fig. 5-(b), -(c), and -(d) of the irreversibility magnetic field H_{irr} versus annealing temperatures T. The part where the rate of decrease increases sharply by four or five times is a weak break-down. The weak break-down occurs at a heat treatment of around 750°C, as shown in Fig. 5-(b), -(c), and -(d) for T = 50 K, 60 K, and 77K, respectively. The weak break-down, however, was not

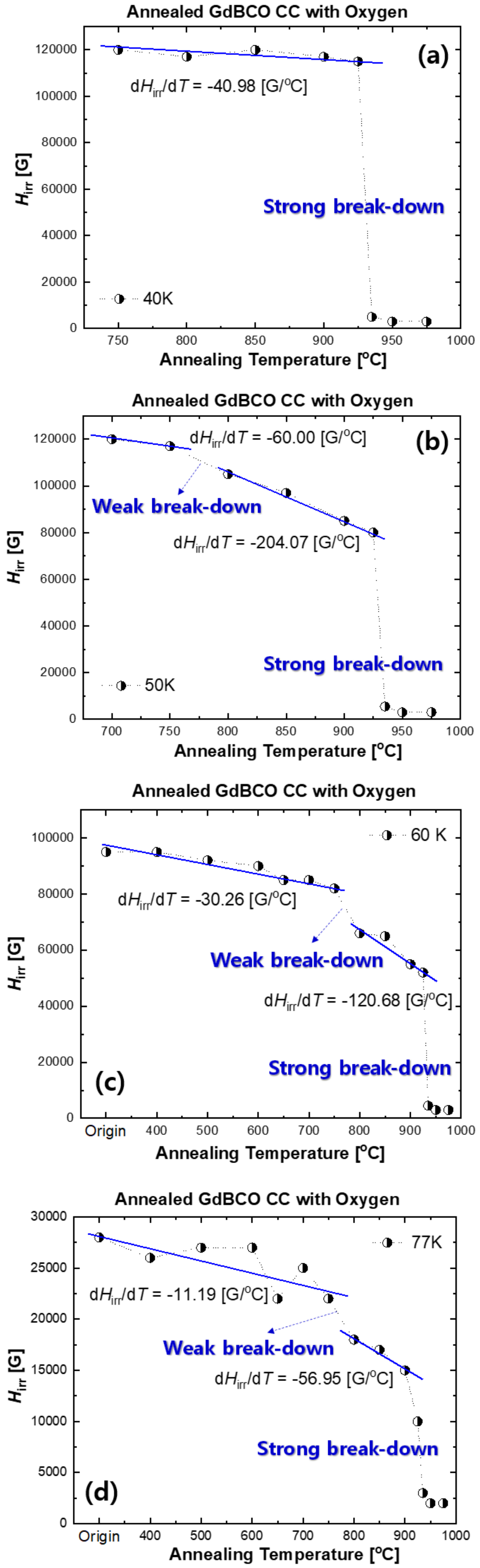

Fig. 5. The irreversibility magnetic field H_{irr} versus annealing temperatures T for both origin and heat-treated O-series of GdBCO CC specimens at temperature (a) T = 40 K, (b) T = 50 K, (c) T = 60 K, and (d) T = 77 K for H parallel to the c-axis.

observed at T = 40 K because the measurements were performed up to applied magnetic field H = 12 T. It is not clear at this time how the weak break-down nature of the heat-treated O-series HTS GdBCO CC specimens according to the annealing temperatures influences the superconducting properties of HTS GdBCO CC tapes. Therefore, additional works to understand the mechanism are underway.

4. SUMMARY

We have reported the magnetic properties of heat treated O-series high temperature superconducting (HTS) GdBCO coated conductor (CC) tapes, which were formed of silver (Ag) protective layer, Ag/GdBCO/Buffer-layers/Stainless Steel. The measurement of the magnetic moment $m(H)$ for heat treated O-series HTS GdBCO CC tapes, were carried out at temperatures – 20 K, 30 K, 40 K, 50 K, 60 K, 70 K, 77 K and 100 K in fields up to 12 T, by employing a PPMS-14 (Quantum Design).

The irreversibility magnetic moment Δm_{irr} was obtained by measuring the magnetic moment $m(H)$ loops. The critical current density J_c values have been estimated from the $\Delta m_{\mathrm{irr}}(H)$ data, using a modified Bean model. The J_c values of 500^{o}C or several heat-treated HTS GdBCO CC specimens are a bit higher than those of the origin HTS GdBCO CC specimen.

The magnetic flux behaviors were investigated from the relationship $J_c \propto H^{-\beta}$. The β values which measures how fast the J_c falls off with annealing temperatures T are found to lower at 500 ~ 600^{o}C when compared to the origin HTS GdBCO CC tapes.

Meanwhile, the irreversibility magnetic field H_{irr} values were estimated from the field at which the Δm_{irr} goes to zero. There are two decreasing rate (dH_{irr} / dT) lines of the H_{irr} values according to increasing the annealing temperatures T. The weak break-down occurs at a heat treatment of around 750^{o}C. In addition, the strong break-down occurs at a heat treatment of above 935^{o}C, which means loss of superconducting properties. The nature of the weak break-down is not clear at this time, and further systematic studies are underway.

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