Electromechanical studies of YBaCuO tape fabricated by metal-organic chemical vapor deposition for coil applications

K. Shikimachi¹, N. Kashima¹, S. Nagaya¹, S. Miyata¹, Y. Yamada¹, T. Izumi¹, K. Nakao¹, Y. Shiohara¹

¹) Chubu Electric Power Co., Inc., 20-1, Kitasekiyama, Ohdaka-cho, Midori-ku, Nagoya 459-8522, Japan
²) Nagoya Coated Conductor Center ISTEC-SRL, 2-4-1 Mutsuno, Atsuta-ku, Nagoya 456-8567, Japan
³) ISTEC-SRL, 1-10-13, Shinonome, Koto-ku, Tokyo 135-0062, Japan

Shikimachi.Kouji@chuden.co.jp

Abstract. YBCO coated conductor has high prospects for coils used in high magnetic fields, but not only its higher transport characteristics but also its adequate workability are required for coil applications. In these studies, mechanical properties of YBCO tape fabricated by multi-stage chemical vapor deposition were investigated by flat-wise and edgewise bend strain tests. After estimation of influences of its bend strain and its self magnetic field, a small coil of the long YBCO tape could be manufactured. Basic characteristics of the coil were investigated and maximum magnetic field of 0.4 T class was achieved in decompressed liquid nitrogen by the small YBCO coil.

1. Introduction

Using YBCO coated conductor, coils in high magnetic fields for superconducting power applications such as superconducting magnetic energy storage (SMES) can be compact and their cost is expected to be lower, because YBCO coated conductor has high critical current density even in high magnetic fields. In that case, adequate workability and less degradation in producing the conductor and manufacturing its coil, as well as its higher transport characteristics and long length are required as quite important parameters. Therefore, coiling technologies of YBCO coated conductor have to be developed aiming at its coil applications.

We have been developing YBCO tape fabricated by depositing a YBCO layer on Hastelloy substrate with PLD-CeO₂ and IBAD-Gd₂Zr₂O₇ buffer layers by a multi-stage metal-organic chemical vapor deposition (CVD) technique and by sputtering silver as a protective and stabilizing layer (hereinafter referred as CVD-YBCO tape) [1]. In the last studies, basic mechanical properties of CVD-YBCO tape were reported [2]. In these studies, mechanical properties of the YBCO tape were investigated further; \( I_c \) decrease in larger bend strain than that of the last studies, YBCO-layer thickness dependency of \( I_c \), and edgewise bend strain dependency of \( I_c \) were investigated. Furthermore, a small coil was manufactured using long CVD-YBCO tape and its basic characteristics were investigated.

2. Mechanical properties of CVD-YBCO tape
2.1. Flat-wise bend strain properties

Flat-wise bend strain tests were conducted with short samples of CVD-YBCO tapes. Critical currents, $I_c$ of CVD-YBCO tape were measured in liquid nitrogen by the standard four-probe method, every time bend strain was given to them at room temperature. Bend strain got higher gradually as it was given in order of decreasing bend diameter. Measured data should be regarded as the lower limit for the tape architecture because of inadvertent damage which may be introduced by the iterative thermal cycling, as well as the mechanical bending and straightening of the samples for each data point. Bend strain ratio was calculated as $t/R$, which was generally reported as an approximation in past reports, where $t$ was thickness of the tape and $R$ was bend diameter.

Flat-wise tensile bend strain tests were conducted until rapid decrease of $I_c$ occurred. $I_c$ when tensile bend strain were given and $I_c$ after they were released were normalized by $I_c(0)$ which was $I_c$ before the first bending. Normalized $I_c$ are shown as a function of bend diameter or strain in figure 1 and 2. A slight increase of $I_c$ can be observed in lower strains. $I_c$ was reversible until over 0.5 percent strain, but after that, $I_c$ was rapidly decreased by over 80 percent at 1 percent strain. Although thicker YBCO layer for higher $I_c$ should be considered, 0.5 percent strain is equivalent to that of 20 mm diameter, which indicates CVD-YBCO tape has promising properties for coil applications.

![Figure 1.](image)

Figure 1. Tensile bend (a) strain and (b) diameter dependencies of normalized $I_c$ of CVD-YBCO/ IBAD tape. (Each thickness of the layers: Ag 15μm/ YBCO 0.5μm/ CeO2 1μm/ GZO 1μm/ Hastelloy 100μm)

$I_c$ of two samples which had different thickness of YBCO layers were measured in the same conditions. The $I_c$ normalized by $I_c(0)$ are shown in figure 2. YBCO-layer thickness dependencies of $I_c$ decrease were evaluated and it was found that maximum reversible strain of three times thinner YBCO layer was about two times larger and its $I_c$ decreased less in irreversible strains.

![Figure 2.](image)

Figure 2. Tensile bend strain dependencies of normalized $I_c$ of CVD-YBCO tapes while bended and after flattened. (Each thickness of the layers: Ag 15μm/ YBCO 0.5, 1.5μm/ CeO2 1μm/ GZO 1μm/ Hastelloy 100μm)

2.2. Edgewise bend strain properties

Edgewise bend strain tests were conducted with short samples of CVD-YBCO tapes in a similar manner to the flat-wise bend strain tests. $I_c$ when bend strain were given and after they were released, normalized by $I_c(0)$, and index value, $n$ are shown in figure 3. $I_c$ was reversible within a tensile bend strain of about 0.6 percent, but was decreased by about 60 percent at a tensile bend strain of 2 percent. Edgewise bend strain dependency of $n$ indicates the similar tendency to that of $I_c$. It should be taken into account in case of detail evaluation that critical current density of the samples was not uniform enough in width direction and its influence might exist.
3. YBCO coil manufacture

3.1. Preparing a small coil of CVD-YBCO tape

Long CVD-YBCO tape was fabricated by multi-stage CVD for a coil. The width of the tape are 10 mm, and the thicknesses of each layer: Hastelloy, IBAD-Gd_2Zr_2O_7, PLD-CeO_2, CVD-YBCO, Ag are 100 \( \mu \text{m} \), 0.65 \( \mu \text{m} \), 0.65 \( \mu \text{m} \), 0.4 \( \mu \text{m} \), 20 \( \mu \text{m} \), respectively. Its \( I_c \) was about 80 A and its index value, \( n \) was about 10. A small YBCO coil was designed and manufactured, considering the \( I_c \) decrease of the coil due to its bend strain and self magnetic field.

3.1.1. Estimation of bend strain of the coil. Before the coil of CVD-YBCO tape was manufactured, bend strain dependencies of \( I_c \) of actual short parts of the long tape for the coil were evaluated, as \( I_c \) decrease depends on thickness of YBCO layer, and so on. The samples received either tensile or compressive bend strain on the YBCO layer. They are shown in figure 4. Difference of \( I_c \) decrease between tensile and compressive strains can be due to remaining compressive strain of YBCO layer caused by the difference of contraction ratios of each layer in the process of fabricating CVD-YBCO tape. Acceptable degradation of \( I_c \) should be determined by considering its application, but if the acceptable \( I_c \) decrease is supposed to be 5 percent, acceptable tensile and compressive bend strains will be 0.7 percent and 0.35 percent respectively.

3.1.2. Trial manufacture of a small coil. The YBCO tape for the coil was wound without strong tension by hand control and impregnated. To estimate degradation in coiling process, we dare to give innermost of the coil maximum compressive strain of 0.34 percent, which is in case of 36 mm diameters. Specifications of the designed coil are listed in table 1 and the manufactured coil is shown in figure 5.

3.1.3. Estimation of self magnetic field. Figure 5 shows magnetic field distribution of the coil when its operating current is 100 A. The magnetic field is highest at innermost in the coil, and fields and its angles at the center and the edge of the innermost are 0.38 T- 0 degree, and 0.32 T- 28 degrees respectively. \( I_c \) of the CVD-YBCO tape due to self field of the coil was estimated to decrease by 35 - 55 percent, referring to evaluated \( J_c - B(\theta) \) characteristics of CVD-YBCO tape [3].
Table 1 Design specifications of the YBCO coil

| Parameter     | Specification          |
|---------------|------------------------|
| Tape type     | CVD-YBCO               |
| Length        | 13.5 m                 |
| Number of turns | 86                    |
| Coil type     | Single pancake         |
| Inner diameter| $\phi$ 36 mm           |
| Outer diameter| $\phi$ 64 mm           |
| Height        | 10 mm                  |
| Max. magnetic field | 3.8 mT/A              |

3.2. Basic characteristics of the YBCO Coil

The coil was tested to check that it was manufactured without unexpected degradation as the design.

3.2.1. Critical current of the YBCO coil. $I_c$ and index value, $n$ measured in liquid nitrogen are shown in figure 7. $I_c$ of the coil at 77 K was 43 A, which value was reasonable, considering $I_c$ decrease from $I_c$ of the tape before coiling by its bend strain and its self magnetic field. $n$ of the coil was about 10, which meant no decrease from $n$ of the tape before coiling. Therefore, it was confirmed that the trial YBCO coil was manufactured without unexpected degradation in a coiling process.

As for temperature dependency of $I_c$ measured in decompressed liquid nitrogen, $I_c$ was increased at lower temperatures and $I_c$ at 65 K was 100 A, which was more than two times $I_c$ at 77 K.

3.2.2. Magnetic field by the YBCO coil. The coil was excited in liquid nitrogen and its magnetic field was measured. Measured magnetic fields when operating currents of the coil were $I_c$ at 77, 70, 67 and 65 K and designed magnetic fields are shown in figure 8. Measured field and designed field were equivalent and it was confirmed that the coil was performed as designed. Maximum field in the coil, $B_{\text{max}}$ and field at the coil center, $B_0$, were 0.38 T and 0.22 T respectively. Magnetic field of 0.4 T class was achieved in decompressed liquid nitrogen by the small YBCO coil.

Acknowledgement

This work was supported by the New Energy and Industrial Technology Development Organization (NEDO) through ISTEC as the Collaborative Research and Development of Fundamental Technologies for Superconductivity Applications.

References

[1] N. Kashima, et al., IEEE Trans. Appl. Supercond., Vol.15, No.2, pp2763-2766, 2005
[2] K. Shikimachi, et al., IEEE Trans. Appl. Supercond., Vol.15, No.2, pp3548-3551, 2005
[3] M. Inoue, et al., Abstracts of the CSJ conference, Vol.72, pp145, 2005