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Abstract—This paper deals with the mechanical strain issue in a high-temperature superconducting (HTS) insert for a GHz-class (> 23.5 T) LTS/HTS NMR magnet. We present results, experimental and analytical, of hoop strainings in a double-pancake (DP) test coil, wound with 6-mm wide YBCO coated conductor (CC) and equipped with strain gauges at their innermost and outermost turns. To keep the YBCO CC to within a 95 %-Ic retention, the conductor tensile strain must be limited to 0.6 %. To satisfy this strain limit in our test DP coil, we wrapped 0.08-mm thick, 6-mm wide stainless steel strip over its outermost turn of an 4.8-mm overband radial build deemed sufficient by our stress analysis based on force equilibrium and generalized Hooke’s law with plane stress approximation. A control test DP coil, actually the same test DP coil, without overbanding, was run under the same experimental condition. In each case the test DP coil was energized up to 350 A at 4.2 K in a background magnetic field of 4 T. We report the experiment and analysis, with discussion on the merit of overbanding as a means to limit hoop strain in high-field HTS inserts.

Index Terms—hoop strain in HTS insert, no-insulation double-pancake coil, overbanding, strain measurement, stress analysis

I. INTRODUCTION

This paper deals with analytical and experimental results of the mechanical strain issue for a high-temperature superconducting (HTS) insert placed in the bore of a low-temperature superconducting (LTS) magnet, specifically an 800-MHz HTS insert (H800) for a 1.3-GHz LTS/HTS NMR magnet, currently in its final stage at FBML [1]-[3]. HTS conductors, YBCO, Bi2223, and Bi2212, have been used for development of high magnetic field applications from several magnet research groups [4]-[14]. Our H800 is an assembly of 94 double-pancake (DP) coils, each wound with 6-mm wide YBCO coated conductor (CC) without turn-to-turn insulation—the so-called NI DP coils. Our stress analysis has shown that overbanding each H800 NI pancake coil will keep the conductor tensile strain within a 95 % Ic retention limit of 0.6 % for this CC [1]. To examine and refine our method of overbanding H800 NI pancakes, we constructed an experimental setup and prepared one NI DP test coil wound with 6-mm YBCO CC and equipped with strain gauges. We used the same NI DP test coil in three test sequences, first the coil overbanding, then, its overbanding unwound, and finally the coil rewound with a lower winding tension. The overband was of 0.08-mm thick, 6-mm wide stainless steel strip of a 4.8-mm radial build. The test DP coil in each case was energized to 350 A at 4.2 K in a background magnetic field of 4 T. We also computed hoop strain by our analytical model based on force equilibrium and generalized Hooke’s law with the plane stress approximation. Experimental and computed strain results show reasonable agreement and are summarized in Section IV. Included also is discussion on the merit of overbanding to limit hoop strain in high-field HTS inserts.

II. ANALYTICAL MODEL

We have developed an analytical model and applied it to compute stress and strain distributions within the winding of a DP coil. The governing equation based on force equilibrium with presence of magnetic force is given as follows [3],[15]-[16]:

\[
r \frac{\partial \sigma_r}{\partial r} + \sigma_r - \sigma_h + rB_z(r) = 0
\]

where \( r, \sigma, J, \) and \( B_z(r) \) are, respectively, radius, stress, current density, and axial magnetic field. To solve (1) by means of generalized Hooke’s law, three basic approximations were established: 1) all shear stresses are zero [16]; 2) the coil is under plane stress condition \( \sigma_{th} = 0 \); and 3) thermal contraction is neglected. Although the thermal contraction generates a considerable strain in the HTS magnet, here we mainly focus on hoop strain induced by electromagnetic forces and cancel out thermal contraction of the test DP coil using a balancing circuit. Eq. (2) is an established matrix to express generalized Hooke’s law based on the above approximations.

\[
\begin{bmatrix}
    \sigma_r \\
    \sigma_h \\
    \sigma_z
\end{bmatrix} = \begin{bmatrix}
    1/E_r & -v_{rh}/E_r & -v_{rz}/E_r \\
    -v_{hr}/E_r & 1/E_h & -v_{hz}/E_h \\
    -v_{hr}/E_r & -v_{hz}/E_h & 1/E_z
\end{bmatrix} \begin{bmatrix}
    \epsilon_r \\
    \epsilon_h \\
    \epsilon_z
\end{bmatrix}
\]

Here, \( \epsilon, E, v \) are, respectively, strain, Young’s modulus, and Poisson’s ratio. With the given mechanical properties of YBCO CC and stainless steel, shown in Table I, to prepare the overbanded NI DP coil used in the first test sequence, (1) was solved to compute stress and strain distributions in the test DP coil.
TABLE I
HTS DOUBLE PANCAKE TEST COIL SPECIFICATIONS

<table>
<thead>
<tr>
<th>Item</th>
<th>Conductor</th>
<th>Overband</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>YBCO CC</td>
<td>Stainless Steel 316</td>
</tr>
<tr>
<td>Width; Thickness [mm]</td>
<td>6.0; 0.075</td>
<td>6.0; 0.080</td>
</tr>
<tr>
<td>Ic (at 77 K, self-field) [A]</td>
<td>&gt; 150</td>
<td>N/A</td>
</tr>
<tr>
<td>E1; E2; E3 [GPa]</td>
<td>73; 142; 134</td>
<td>180; 180; 180</td>
</tr>
<tr>
<td>Vao; Voo; Voa [Null]</td>
<td>0.40; 0.35; 0.18</td>
<td>0.3; 0.3; 0.3</td>
</tr>
<tr>
<td>Winding tension [N]</td>
<td>49</td>
<td>49</td>
</tr>
<tr>
<td>Coil</td>
<td>Double Pancake Winding</td>
<td></td>
</tr>
<tr>
<td>ID; OD; Height [mm]</td>
<td>91.0; 105.1; 12.1</td>
<td></td>
</tr>
<tr>
<td>Number of turn</td>
<td>188</td>
<td></td>
</tr>
<tr>
<td>Conductor Length [m]</td>
<td>57.8</td>
<td></td>
</tr>
<tr>
<td>Inductance [mH]</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>Magnet constant [mT/A]</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Re&lt;sup&gt;a&lt;/sup&gt; [mΩ]</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Overband; Number of turns</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Re is characteristic resistance of no-insulation coil [17].

Fig. 1. NI DP test coil wrapped with stainless steel overband. A 0.5-mm thick stainless steel inner bobbin has slots machined to install strain gauges for strain measurement at the test coil innermost turn.

III. EXPERIMENTAL SETUP

A. NI DP Test Coil

Fig. 1 is a picture of the overbanded NI DP test coil. The coil was wound, with a tension of 49 N, on a 0.5-mm thick stainless steel bobbin. The inner bobbin has four 3.5-mm wide, 12-mm long slots machined out, through which 4 strain gauges were mounted to measure hoop strains at the coil innermost turn. Four strain gauges were also mounted at the coil outermost turn. The test coil and overband were wound with a winding tension of 49 N for the first test sequence. Then the overband was removed to measure hoop strain of the test coil without overband. In the final test sequence, the test DP coil itself was re-wound with a tension of 9.8 N without overband to examine the effect of winding tension on hoop strain.

B. Wheatstone Bridge Circuit for Strain Measurement

The hoop strains were measured with Wheatstone bridge (WB) circuit, shown in Fig. 2. The shaded blue area is at 4.2 K, and \( R_{\text{gauge}} \) represents one of the strain gauges on the test coil. The WB circuit converts a hoop-strain-induced resistance change in \( R_{\text{gauge}} \), \( DR \), to a change in its output voltage, \( V_{\text{out}} \). The output voltage measurement setup, at room temperature, is located away from the 4.2-K environment where the strain signals are generated; three extension lines of line resistances (\( R_{\text{line1}}, R_{\text{line2}}, \) and \( R_{\text{line3}} \)) connect the two environments. To cancel out extraneous signals induced by mechanical, thermal effects and the extension lines, the measurement circuit includes a balancing circuit of three resistors (\( R_1, R_2, \) and 10 k\( \Omega \)) and a 100-k\( \Omega \) potentiometer. The effective resistances of \( R_1 \) and \( R_2 \) (\( R_{1E} \) and \( R_{2E} \)), adjusted by the potentiometer, were in the range 366-380 \( \Omega \). Before every experimental trial, we used the balancing circuit to make \( V_{\text{out}} \) under 10 \( \mu \)V for accurate strain measurement, most importantly to minimize all extraneous signals.

C. Strain Gauge Selection

A commercial strain gauge meeting our experimental setup requirements was selected for this experiment. The gauge’s specifications are listed in Table II. The gauge needed to be narrow enough to be mounted, through a slot in the stainless steel bobbin, on the innermost turn of the test coil and its grid material needed to meet 4.2-K environment. We also checked

TABLE II
STRAIN GAUGE SPECIFICATIONS

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Micro-Measurements</td>
</tr>
<tr>
<td>Part Number</td>
<td>WK-06-031DE-350</td>
</tr>
<tr>
<td>Matrix Width; Length [mm]</td>
<td>3.0; 6.9</td>
</tr>
<tr>
<td>Gauge Width; Length [mm]</td>
<td>0.81; 0.79</td>
</tr>
<tr>
<td>Temperature range [K]</td>
<td>4.2 ~ 563.2</td>
</tr>
<tr>
<td>Gauge resistance [Ω]</td>
<td>350.0 ± 0.4 %</td>
</tr>
<tr>
<td>Strain range [%]</td>
<td>± 1.5</td>
</tr>
<tr>
<td>Gauge factor (GF) [Null]</td>
<td>2.06 ± 1.0 %</td>
</tr>
</tbody>
</table>
its magnetoresistance in the field range 0–4 T. Fig. 3 presents measured gauge \( V_{\text{out}} \) (red trace; open circles) as the background magnetic field (black trace; squares) was swept over the field range. The field dependence of \( V_{\text{out}} \), as seen in Fig. 3, is insignificant enough for magnetoresistance to be neglected in our experiment.

D. Conversion of \( V_{\text{out}} \) to Mechanical Strain

The gauge resistance change (\( \Delta R \)) induced by hoop strain (\( \epsilon_h \)) can be expressed as follows:

\[
\Delta R = R_{\text{gauge}} \times GF \times \epsilon_h
\]

where \( R_{\text{gauge}} \) and \( GF \) are strain gauge resistance and gauge factor, respectively. Assuming that those three extension lines resistances are negligibly smaller than \( R_{\text{gauge}} \) and \( R_{\text{dummy}} \), \( V_{\text{out}} \) can be expressed as:

\[
V_{\text{out}} = \left( \frac{R_D}{R_D + R_G + \Delta R} - \frac{R_{2E}}{R_{1E} + R_{2E}} \right) \times V_{PS}
\]

where \( R_{1E}, R_{2E} \), and \( V_{PS} \) are, respectively, effective leg resistance of \( R_1 \), effective leg resistance of \( R_S \), and power supply voltage for the bridge circuit, 3V. With another assumptions that the WB circuit is well balanced and \( R_{\text{dummy}} \approx R_{\text{gauge}} \), (4) can be derived to express relation of \( V_{\text{out}} \) and \( \epsilon_h \) as follows:

\[
V_{\text{out}} \approx \left( -\epsilon_h \times GF \frac{4}{4 + 2 \cdot \epsilon_h \times GF} \right) \times V_{PS}
\]

E. Experimental Procedure

The NI DP test coil was operated in a bath of liquid helium at 4.2 K and placed in a background magnetic field of 4 T. The electromagnetic forces were induced by the operating current which was increased through a series of ramp-and-pause steps.

IV. Experimental Results

As stated above, the NI DP test coil was operated sequentially, in each sequence with a different condition: 1) the test coil wound with a 49-N winding tension, and over-banded with the same winding tension (OB5); 2) unbanded (UB5); 3) rewound test coil with a tension, 9.8 N, without overband (RUB1). In each condition, the test coil was tested repeatedly. Fig. 4 presents temporal traces for OB5 placed in a background field of 4 T: operating current (black); center field (blue); hoop strains at the innermost (red) and at the overband (green) turns. The operating current was increased stepwise at a 50-A increment, holding the current for 1 minute at each step, up to 350 A. Because of short time constant of the NI test coil, there was no significant time lag between magnetic field and current. The coil current, converted from magnetic field, and hoop strain, converted from \( V_{\text{out}} \), were averaged and summarized in Fig. 5 and Fig. 6.

A. Hoop Strain at Innermost Turn

Fig. 5 presents a summary of the innermost turn hoop strain as a function of coil current, both computed and measured, of the test coils having the three different conditions. Computed strains of OB5 (red line) and UB5 (dashed black line) are both depicted in Fig. 5. The computed hoop strains at 350 A showed a significant difference between OB5 and UB5, 0.07% vs. 0.12%, which clearly demonstrates that the overbanding is effective in reducing the hoop strain at the coil innermost turn.

Measured results, however, showed rather a different tendency. The measured hoop strains from OB5 (red circle symbol), UB5 (black and blue square symbols), and RUB1 (green triangle symbol) are nearly the same up to 250 A. The UB5 was tested twice as shown in Fig. 5 to confirm this tendency and the second UB5 test was similar up to 250 A. However, the second trial of UB5 (blue; half-filled squares) also showed slightly higher strain with larger spread of hoop strain measured at a similar coil current. Because the measured results might be related to friction between adjacent turns, we decided to reduce this friction by lowering the
winding tension of the test coil from 49 N to 9.8 N. Fig. 5 shows the measured result of RUB1. For coil current up to 250 A, RUB1 also showed values similar to those of OB5 and UB5, but at 325 A it produced a strain larger than the other test conditions.

B. Hoop Strain at Outermost Turn

Fig. 6 presents a summary of hoop strains at the outermost turn of the three conditions, correlated with coil current and computed and measured. In view of the 95%-Ic retention limit, the outermost turn strain is less important than the innermost turn strain. But, there are two observations worth noting: 1) most measured data show lower values than computed, which may imply the presence of additional forces not included in our analysis; 2) data from unbounded cases, UB5 and RUB1, are more scattered than those from OB5.

C. Further Discussion on Experimental Results

In this paper, we believe that this experiment-analysis discrepancy and the phenomenon of a sudden increase in hoop strain are related and likely caused by turn-to-turn friction, either its restraining force and/or transitory slippage. This is because the axial pressure in the test coil is negligibly small, ~1 kPa. Friction is often intractable for precise computation and excluded in our first analytical model. Its effect, however, may be included approximately in our model through the radial stress distribution induced by winding tension. Computed radial stress distribution vs. radial distance plots of the three test conditions are shown in Fig. 7. The RUB1 radial stress is significantly lower than those of OB5 and UB5 throughout the winding, and this might be a reason for the largest strain in RUB1 above 250 A.

V. CONCLUSION

This paper presents results of a work to measure and compute strain induced by magnetic force on an HTS NI DP test coil. Our analytical results demonstrate that overbanding is beneficial to HTS DP coil. Although our experimental results are still preliminary, we may conclude that an overbanding technique to be deployed to every single pancake of all 94 DP coils in H800 of our 1.3-GHz NMR [2] will keep H800 mechanically intact. However, to validate the benefit of overbanding, it is also clear that our work on this technique must further be refined and upgraded, specifically: 1) inclusion of friction in our analytical model; 2) experimentation with larger test coils in a higher magnet field to subject the YBCO CC to a greater magnetic hoop strain.

REFERENCES


