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NEW MULTIFILAMENTARY SUPERCONDUCTING WIRES WITH FILAMENT OF Nb$_3$Sn IN SITU WIRES

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Résumé - Nous proposons un nouveau type de conducteur supraconducteur multifilamentaire utilisable pratiquement. Il s’agit d’un fil dans lequel les filaments sont formés in situ par un procédé de diffusion interne.

Abstract - As a superconducting in situ wire for a practical use, we propose a new type of a multifilamentary wire, i.e., a stuck wire with fine cores which consist of in situ processed wires of an internal diffusion type.

Although in situ processed Nb$_3$Sn wires have merits in their simpler fabrication processes and smaller stress effects on the critical current density, they have not been manufactured for a practical use. This is because they have demerits in their lower critical current densities, smaller current capacities per a wire, and extremely larger hysteresis losses similar to that of a single-core superconductor /1,2/.

The purpose of this paper is to propose a new type of practical in situ Nb$_3$Sn wires with a large current capacity and a low ac loss. For this purpose, we at first studied experimentally electromagnetic properties of a single in situ wire. Using the obtained results, we discuss the design principle of a new type wire. A test wire was manufactured to examine our design principle.

I - ELECTROMAGNETIC PROPERTIES OF A SINGLE in situ WIRE

In this section, we discuss the electric coupling among Nb$_3$Sn filaments in a single in situ wire which plays the role of a fine core in the present type of stuck wire.

We prepared in situ processed Nb$_3$Sn wires of internal diffusion type. As illustrated schematically in Fig.1, the region 2 is occupied by Cu-22wt%Nb fabricated by the arc melting method. The center of this part was drilled and a Cu hollow cylinder filled up with 60vol%Sn-prepacked Cu powder /3/ was inserted into this drilled space. Then they were mounted inside a Cu-10wt%Ni jacket, which is expected to prevent the wire from breaking during the cold drawing process. Initial and final diameters of the wire are 12.5 mm and 0.3 mm, respectively, and the resulting reduction ratio is about 1700. The sample wires were wound into single-layered, solenoidal coils with the diameter of 35 mm and the heat treatment was carried out after the winding.

Effective diameter at high fields: As a quantitative measure of the coupling among Nb$_3$Sn filaments, the parameter $d_{\text{eff}}$ called the effective diameter has often been used. According to Shen's definition /2/, $d_{\text{eff}}$ is given by

$$<M>_{2R}^2 = \frac{2}{3\pi} \nu_0 \mu_0 <J_c>_{2R} d_{\text{eff}},$$

where $<M>_{2R}$ and $<J_c>_{2R}$ are the transverse magnetization and the critical current density averaged over the region of $0 \leq r \leq R$ shown in Fig.1 respectively, and $\nu = 1$ is a
correction factor taking account of the effects of the inner bronze region. Measurements were carried out for the cases of the external trapezoidal fields with a height of $B_m = 0.1$ T or 0.2 T and a minimum rise or fall time of 1 sec superposed onto the various bias fields of $B_{dc} = 6 \sim 12$ T. The observed curves of minor magnetization had no sweep-rate dependences. With the aid of the data, the values of $d_{eff}$ were calculated from Eq. (1) and are plotted against bias field in Fig. 2. We can find the value of $d_{eff}$ is given by $d_{eff}/2R \sim 0.7$ over the range of $6 \sim 12$ T. Thus, we can conclude that the electromagnetic behaviors of the in situ wire are quite similar to those of the single-core superconductor even at high fields.

**Effective diameter in the presence of transport currents:** In order to investigate the effect of transport currents on $d_{eff}$, we measured the loss of an in situ wire carrying a dc transport current in external transverse pulse-fields. Measurements were carried out for the sample coils No.A3 and A3' by the so-called coil-simulation method /4/ in the bias transverse field of 2 T. In Fig.3(a) and (b), observed magnetization losses and dynamic resistance losses /5/ are shown, respectively. It must be noted that these data are independent of the sweep rate within the present experimental accuracy. We can use theoretical expressions derived by Ogasawara et al. /5/ if we assume that the electromagnetic behavior of in situ wires is the same as that of a single-core superconductor with the diameter of $d_{eff}$, and the theoretical results show good agreements with observed data.

**II - EXPECTED PROPERTIES OF A STUCK WIRE WITH MANY FINE in situ Nb$_3$Sn CORES**

In this section, we shall show some examples of design of the present type of in situ stuck wire taking account of the purpose of its application for high-field pulse magnets. An example of the design in this case is shown in Table II, where the Nb content in CuNb is supposed to be as high as 35 wt% in order to have a large current density.

The first principle on the design of the present stuck wire is to optimize the amount of the hysteresis loss compared with the coupling-current loss among in situ cores. It must be noted that the present stuck wire is also twisted in the same manner as the ordinary multifilamentary wire to decrease the coupling current loss. We assumed, therefore, that ac losses in the present wire can also be estimated by the existing theories on the ordinary multifilamentary wire, which will be confirmed experimentally in the next section. The values of losses were estimated for the external field conditions for windings of a high-field condition as $B_{dc} = 12$ T, $B_m = 0.5$ T and $t_i = 0.1$ sec which are typical conditions for windings of a high-field pulse magnet in Kyushu University /6/. We can find that the hysteresis loss is slightly smaller than the coupling loss, which seems to be an optimized design under a given amount of total loss.

The second principle in the present design is related to the electromagnetic properties in the presence of the transport current. In this case, it has been pointed out by us /7/ that the current uniforming time-constant $\tau_{10}$ defined by

$$\tau_{10} = \frac{R_b^2}{2\pi R_b \sqrt{\pi R_b}} \frac{B_m}{t_i}$$

(2)

should be taken into account to discuss the current distribution in multifilamentary wires, where $R_b$ is a radius of a core bundle and $\lambda$ is the volume fraction of cores with a radius of $R$. Under the condition of $\tau_{10} \gg t_i$, the transport current distributes uniformly. When $\tau_{10} \ll t_i$, on the other hand, a localized transport current flows near the wire surface. Since the localized current distribution has a strong possibility for the occurrence of flux jumps and of a large dynamic resistance loss, the value of $\tau_{10}$ should be designed as small compared with the rise or the fall time $t_i$ in order to use the wire in the concerned pulse magnet. Compared with ordinary Nb$_3$Sn multifilamentary wires in which $\tau_{10}$ is quite long due to the small filament diameter limited to a few microns or so by a short diffusion length of Sn in Nb, we can say that the present type of in situ stuck wire has flexibility in its design for various applications.
III - ELECTROMAGNETIC PROPERTIES OF A TEST WIRE

In order to confirm the design principle in the in situ stuck wire mentioned in the previous section, we manufactured a test wire of the present type. We, at first, prepared 19 in situ Nb3Sn wires with 1.5 mm in diameter in the same manner as mentioned in the previous section. Next, each in situ wire was shaped into the one with a hexagonal cross section. These shaped in situ wires were stuck inside the Cu-30wt%Ni jacket, together with 12 dummy Cu-10wt%Ni wires as a spacer. The obtained composite in this way was drawn to a wire of 1.5 mm in diameter. Final diameters of the in situ bundle and each in situ core were 740 μm and 110 μm, respectively, and a reduction ratio was about 7000. After twisting the wire (L = 90 mm), the heat treatment was carried out at 600°C during 80 hours (Fig.4).

The coupling time-constant \( \tau_c \) can be determined from the frequency characteristic curve of coupling current losses in the small ac field case /8/. In Fig.5(b), the observed frequency dependence of the ac loss per cycle per unit volume of the in situ core bundle, \( w(f) \), is shown, where the fields amplitude was 0.3 mT and \( B_{dc} = 2 \text{T} \). Since the measured frequency region of \( f = 0.5 \sim 10 \text{Hz} \) was not sufficiently wide to determine the coupling time-constant directly by the observed data, we estimated the experimental value of the coupling time-constant with the aid of the existing theoretical expressions. The peak frequency \( f_{c1}^p = (2\pi/2\tau_c)^{-1} \) was determined by searching the best fit between the observed curve of \( w_c(f) \) and the theoretical one, and the result is given by \( f_{c1} = 166 \text{Hz} \). From the comparison of \( \tau_c \) between this experimental value (0.96 sec) and the theoretically designed value (0.92 sec) by using the conductivity of the CuNi, i.e., \( \sigma_m = 7.1 \times 10^6 \Omega^{-1} \text{m}^{-1} \), it is concluded that our design of the coupling time-constant is quite satisfactory.

Measurements of the transverse magnetization \( \langle M \rangle_{2R} \) was also carried out in a bias field of 2 T. We obtained \( \langle M \rangle_{2R} = 15.3 \text{mT} \) independently of the sweep rate \( <0.05 \text{T/sec}> \). It is to be noted that \( t_s = 2 \text{sec} \) for the magnetization measurement is much longer than the observed coupling time-constant of \( \tau_c \). Thus the external pulse field with the sweep rate of 0.05T/sec penetrated fully into the stuck wire, and hence the observed data of the magnetization is expected to be explained by the calculated value of the magnetization from all in situ cores.

For the present test wire, the critical current density averaged over the core region in the stuck wire was given as \( <J_c>_{2R} = 2.2 \times 10^8 \text{A/m}^2 \) at 2 T. This small value may be attributed to a failure of the heat treatment or drawing by handiwork in manufacturing the test wire. Substituting this value of \( <J_c>_{2R} \) and \( d_{eff}/2R = 1 \) into Eq.(1), we obtained the theoretical value of the magnetization as 6.3 mT. The deviation of this order between theory and experiment may be accepted by taking account the unevenness of the shape of each in situ core.

IV - CONCLUSION

The stuck wire with many in situ processed Nb3Sn cores of an internal diffusion type proposed in this paper as a practical in situ wire seems to have remarkable merits in i) simpler fabrication and ii) flexible design.

References

/7/ Sumiyoshi, F., Koga, K., Hori, H., Irie, F., Kawashima, T. and Yamafuji, K.
TABLE I Parameter of in situ wires

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>2R [μm]</th>
<th>2ra [μm]</th>
<th>Tp [mm]</th>
<th>Heat treatment</th>
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<tr>
<td>A1</td>
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<td>125</td>
<td>-</td>
<td>558 100</td>
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<tr>
<td>A3</td>
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<td>125</td>
<td>77</td>
<td>627 168</td>
</tr>
<tr>
<td>A3'</td>
<td>200</td>
<td>125</td>
<td>-</td>
<td>627 168</td>
</tr>
<tr>
<td>A4'</td>
<td>200</td>
<td>125</td>
<td>-</td>
<td>600 100</td>
</tr>
<tr>
<td>B2</td>
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<td>140</td>
<td>77</td>
<td>559 168</td>
</tr>
<tr>
<td>B3</td>
<td>225</td>
<td>140</td>
<td>-</td>
<td>575 168</td>
</tr>
</tbody>
</table>

**Fig.1** Cross section of the in situ wire.

1. Cu-10wt%Ni
2. Cu-22wt%Nb
3. Cu
4. Cu+60vol%Sn

**Fig.2** Dependence of \( d_{eff}/2R \) on \( B_{dc} \)

**Fig.3** \( B_m \) dependences of the magnetization loss \( W_m \) and the dynamic resistance loss \( W_d \).

**Fig.4** Photograph of the cross section of the in situ stuck test wire.

**Fig.5** Frequency dependence of the ac loss in the stuck wire, where • — \( W(f) \), ○ — \( W(f)-W(0) \).

The solid line represents the theoretical values of \( W_C(f) \).