Evaluation of Layer Thickness Dependence of Critical Current Density using Longitudinal Magnetic Field Effect in Superconducting Coated Conductors

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Abstract. When the critical current density \( J_c \) for a superconductor is constant, the critical current \( I_c \) increases in proportion to the superconducting cross-sectional area. However, in the case of a superconducting coated conductor, when the thickness of the superconducting layer exceeds about 2 µm, there is no further increase in \( I_c \). This is because \( J_c \) decreases due to the structural degradation of the superconducting layer. In this study, \( J_c \) for samples with superconducting layers of different thicknesses was measured using the longitudinal magnetic field effect in order to investigate the optimum layer thickness for maximizing \( I_c \). Differences in the \( J_c \) characteristics due to the layer thickness appeared more clearly under a longitudinal magnetic field than a transverse magnetic field. This was particularly true at low temperatures, and the optimum layer thickness was found to be approximately 1 µm.

1. Introduction

The critical current \( I_c \) for a superconducting coated conductor initially increases with increasing superconducting layer thickness, but then fails to increase any further. This is because the critical current density \( J_c \) decreases due to the structural degradation of the superconducting layer [1]. The layer thickness dependence of \( J_c \) has previously been investigated under a transverse magnetic field, and \( J_c \) was found to exhibit a maximum for a superconducting layer thickness of about 2 µm [2-3].

An external magnetic field was applied to the superconductor either in the transverse direction (perpendicular to the current-flow direction) or the longitudinal direction (parallel to the current-flow direction). It is known that when the current and the magnetic field are parallel, \( J_c \) increases with increasing magnetic field strength. This is known as the longitudinal magnetic field effect [4-7], and is associated with a reduction in the Lorentz force. As a practical application of this effect, a force-free superconducting electrical transmission cable has been proposed [8]. Therefore, a superconducting wire with a high critical current due to the longitudinal magnetic field effect is desirable.

By examining the layer thickness dependence of the longitudinal magnetic field, it is possible to determine whether the current and the magnetic field are parallel. It has been reported that for a bulk rare-earth based superconductor, \( J_c \) is larger under a longitudinal magnetic field than a transverse magnetic field at low temperatures [9]. A similar situation was found for rare-earth based superconducting thin films [10-12]. It is reported that the decrease of the critical current density in the...
longitudinal magnetic field means that the current and the magnetic field are not parallel, i.e., the structure of the superconducting layer is degraded [11-12].

In the present study, the dependence of $J_c$ on the superconducting layer thickness was investigated using the longitudinal magnetic field effect. Furthermore, the crystal orientation of the superconducting coated conductor was investigated to determine the optimum thickness of the superconducting layer.

2. Experimental Methods

The sample used in the present study was a Gd-based coated conductor obtained by forming an intermediate layer on a Hastelloy substrate by ion beam assisted deposition (IBAD), and producing a superconducting layer using pulsed laser deposition (PLD) [13].

Figure 1 shows the dependence of $I_c$ on the position in the sample, measured using the TapeStar™ system. The thickness of the superconducting layer varied depending on position, and four sample regions (labelled A to D) were selected for use in the measurements. The thickness of the layer was estimated based on the number of PLD shots. Table 1 shows the superconducting layer thickness and $I_c$ for each sample region. Since these samples were difficult to measure in the case of high $I_c$, the width of the superconducting layer was reduced from 12 mm to 0.3 mm by wet etching. Table 2 shows the calculated and measured values for $I_c$ for the samples after etching. Given that all the measured values were within the expected range, etching was considered to be successful.

The $J_c$-$B$ characteristics of the samples were measured under an applied magnetic field $B$ of up to 0.5 T at 65.0, 70.0, and 77.3 K using a four-terminal method in liquid nitrogen. A superconducting magnet was used to apply the magnetic field [14].

![Figure 1. Dependence of minimum (blue) and maximum (red) values of $I_c$ on sample position for superconducting coated conductor.](image)

| Sample | Thickness [μm] | $I_{c_{\text{min}}}$ [A] | $I_{c_{\text{max}}}$ [A] |
|--------|----------------|--------------------------|--------------------------|
| A      | 0.6            | 60                       | 100                      |
| B      | 0.9            | 140                      | 190                      |
| C      | 1.2            | 240                      | 300                      |
| D      | 1.5            | 300                      | 380                      |

Table 1. Superconducting layer thickness, minimum critical current $I_{c_{\text{min}}}$, and maximum critical current $I_{c_{\text{max}}}$ for four 12-mm-wide samples.
3. Results and Discussion

Figure 2 shows the $J_c$-$B$ characteristics at 77.3 K under longitudinal and transverse magnetic fields. $J_c$ for sample A was smaller than that for the other samples, probably because the superconducting layer was too thin in the former sample and crystal growth was insufficient. As the magnetic field increased, the difference in $J_c$ under longitudinal and transverse magnetic fields increased, indicating that the longitudinal magnetic field effect occurred. $J_c$ for samples B, C, and D decreased in a similar manner under longitudinal and transverse magnetic fields, indicating no layer-thickness dependence. Therefore, it was difficult to determine the optimal thickness of the superconducting layer.

Figure 3 shows the $J_c$-$B$ characteristics at 65.0 K under longitudinal and transverse magnetic fields. Under a longitudinal magnetic field, $J_c$ for sample D decreased with increasing field strength, unlike the case for samples B and C. This is likely due to increased structural degradation of the superconducting layer as it becomes thicker, as previously reported [9-12]. In this situation, the current and magnetic field are no longer parallel, which weakens the longitudinal magnetic field effect. Therefore, the superconducting layer thickness in sample D is above optimal, whereas that in samples B and C is optimal.

Figure 4 shows the $J_c$ characteristics for different superconducting layer thicknesses $t$ at 0.5 T under longitudinal and transverse magnetic fields at various temperatures. There was no difference among samples B, C, and D at 77.3 K. However, $J_c$ for sample D decreased under a longitudinal magnetic field at lower temperatures of 65.0 and 70.0 K. This means the longitudinal effect is weakened and the structure of the superconducting layer is degraded [11-12]. On the other hand, $J_c$ for sample D did not decrease under a transverse magnetic field at low temperatures, and no clear layer thickness dependence was observed. Thus, by using the longitudinal magnetic field effect, the difference in the $J_c$-$B$ characteristics due to layer thickness became more clear. From these results, it can be concluded that the optimum layer thickness under a longitudinal magnetic field was 0.9 – 1.2 μm.

For the force-free superconducting electrical transmission cable described in the introduction, the operating temperature is assumed to be 77.3 K. Therefore, even if a superconducting layer thickness of 1.5 μm is used, as in the case of sample D, there should be no problem. Thus, it will be necessary to measure thicker samples in the future. Finally, in order to determine the peak $J_c$ value more accurately, samples should be prepared with even finer thickness intervals.

| Sample | $I_{c_{\text{min}}}$ [A] | $I_{c_{\text{max}}}$ [A] | $I_c$ [A] |
|--------|--------------------------|--------------------------|---------|
| A      | 1.50                     | 2.50                     | 1.77    |
| B      | 3.50                     | 4.75                     | 4.66    |
| C      | 6.00                     | 7.50                     | 6.20    |
| D      | 7.50                     | 9.50                     | 7.67    |

Table 2. Calculated and measured $I_c$ values for each sample after etching to a width of 0.3 mm.
Figure 2. $J_c$-$B$ characteristics at 77.3 K. The solid lines are for a longitudinal magnetic field, and the broken lines are for a transverse magnetic field. $J_c$ for sample A is smaller than that for the other samples. $J_c$ behaves differently under longitudinal and transverse magnetic fields due to the longitudinal magnetic field effect.

Figure 3. $J_c$-$B$ characteristics at 65.0 K. As the longitudinal magnetic field increases, $J_c$ for sample D decreases more than that for samples B and C. When the superconducting layer is thick, the structural degradation of the superconducting layer occurs. As the transverse magnetic field increases, $J_c$ for samples B, C, and D decreases in a similar manner.

Figure 4. Dependence of $J_c$ on superconducting layer thicknesses $t$ at 0.5 T and various temperatures under longitudinal and transverse magnetic fields. There is no difference in $J_c$ for $t = 0.9 - 1.5 \mu m$ at 77.3 K. However, $J_c$ exhibits a peak for $t = 0.9 - 1.2 \mu m$ at 65.0 K and 70.0 K under a longitudinal magnetic field.
4. Conclusion

The effect of the superconducting layer thickness on the $J_c$-$B$ characteristics was investigated using the longitudinal magnetic field effect. When the layer was too thin, crystal growth was insufficient and $J_c$ was small. When it was too thick, $J_c$ decreased under high magnetic fields due to the structural degradation of the superconducting layer. This did not occur under a transverse magnetic field. Using the longitudinal magnetic field effect, the optimal superconducting layer thickness for achieving the highest $J_c$ was found to be about 1 µm at 65.0 K. However, to obtain more precise results, it is necessary to measure even thicker samples using smaller thickness intervals.

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