

# Critical Currents and AC Losses in Coated Conductors

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**Abstract**— Numerical simulation on AC loss analysis has been carried out based on the critical state model as well as taking into account nonlinear  $E$ - $J$  characteristics as a function of magnetic field and temperature within the framework of the percolation transition model. Influence of multiple tape stacks, magnetic field dependence and the effect of  $J_c$  improvement of magnetization losses in a high field magnet have been discussed based on the numerical analysis. Influence of spatial  $J_c$  non-uniformity has also been studied by the magnetic microscopy and its influence on AC losses in multi-filamentary tape has been discussed.

## I. INTRODUCTION

Influence of tape stacks on AC losses will become relevant in practical application of coil windings and magnets. Also magnetic field dependence of  $J_c$  on AC losses should be taken into account for magnet applications. Based on the comprehensive analysis on transport  $E$ - $J$  relationship in GdBCO coated conductor, we estimated AC losses by use of numerical analysis. Spatial  $J_c$  non-uniformity also becomes critical issues especially in the case of multi-filamentary tapes. We visualize local current flow by solving inverted Biot-Savart's law from magnetic microscopy.

## II. NUMERICAL ANALYSIS OF AC LOSSES IN THIN STRIPS

### A. Influence of Tape Stacks

Numerical simulation has been carried out assuming constant  $J_c$  in 1 cm-wide thin strip. For the case of single layer, calculated losses show good agreement with theoretical expression for both transport loss and magnetization loss. As a next step, we calculated current profile in the case of multiple layers under the same amplitude of alternating magnetic field,  $B_{AC}=0.01$  T. As the number of layer increases, the external field is shielded more effectively, therefore the magnetization loss becomes smaller. The current profile approaches similar to the case of slab if the numbers of stacks increase. Typical examples are shown in Fig. 1.

### B. Influence of Magnetic Field Dependent $I_c$

It has been reported that AC losses deviate from theoretical expression in the region of high magnetic field amplitude because we can not assume constant  $I_c$  anymore [1]. Using the percolation transition model, we describe temperature- and

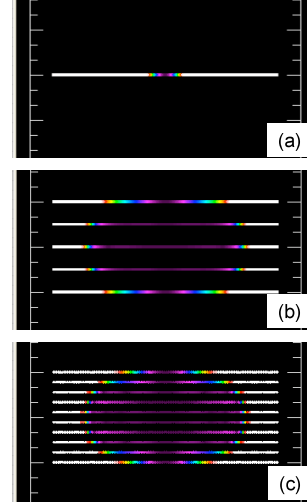


Fig. 1. Current profile in 1 cm-wide thin strips obtained from numerical simulation assuming critical state model. (a) single layer,  $I_c=100$  A, (b) 5 stacks having 1 mm separation with  $I_c=100$  A each, i.e., total  $I_c=500$  A. (c) 10 stacks having 0.5 mm separation with  $I_c=50$  A, namely total  $I_c=500$  A is the same to the case of (b).

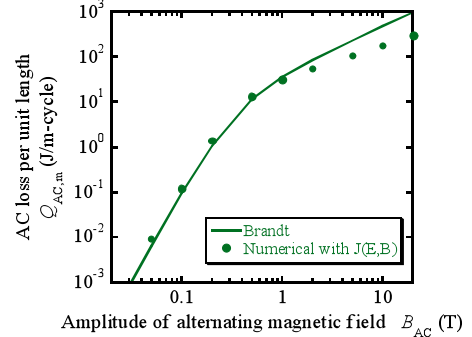


Fig. 2. Magnetization loss obtained by the numerical simulation taking into account magnetic field dependent  $E$ - $J$  relationship at 4.2 K.

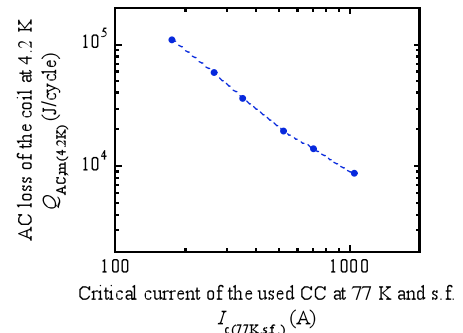


Fig. 3. Magnetization loss estimated in 40 T class magnet as a function of  $I_c$  of tape strand

magnetic field-dependent  $E$ - $J$  characteristics analytically [2, 3]. Using those relationships in GdBCO tape, we calculated magnetization loss in thin strip. The result is shown in Fig. 2. We can see the deviation from the expression by Brandt at high field region whereas we can neglect the influence of field dependence of  $J_c$  at low magnetic field.

### C. Impact of $I_c$ Improvement on AC Losses in Magnets

As is well established, magnetization loss in high AC external field (higher than full penetration field) increases when  $J_c$  increases. On the other hand, total the volume of the magnet can be reduced significantly if the  $I_c$  value of the strand increases. As a result, total AC losses can be reduced if the  $I_c$  value increases. As an example, estimation of AC losses in 40 T class high field magnet operating at 4.2 K is shown in Fig. 3, where the current carrying capability at 4.2 K is estimated from the  $I_c$  value at 77K, s.f. condition based on transport measurements and analysis using GdBCO tape.

## II. INFLUENCE OF $I_c$ NON-UNIFORMITY

Magnetic microscopy allows us to visualize local current flow [4, 5]. Making a model multi-filamentary structure, we investigate current flow as shown in Fig. 4. When a filament was cut perfectly as in #2, bias current cannot flow at the filament but shielding current is induced inside the filament. This means that magnetization loss will be induced whereas the filament cannot carry transport current.

Detailed feature of the filamentary current flow can also be visualize by the Magneto scan as shown in Fig. 5 where we induced shielding current by a permanent magnet mounted near the Hall probe [6]. This is very promising technique to investigate filamentary structure since we can estimate contact less and without any bias current.

## III. SUMMARY

Multiple tape stack results in lower AC loss at low  $B_{AC}$ , however there is not much influence when  $B_{AC}$  is higher than full penetration field.  $I_c$  enhancement is effective to reduce AC losses in magnets or coil windings.

Magnetic microscopy is very effective way to analyze local current flow in CC. Striated multi-filamentary structure is one of the strategies to reduce AC losses. However, spatial  $I_c$  non-uniformity results in lower current carrying capability while AC losses are generated.

Reliable process to obtain uniform  $I_c$  and striation in long length tape must be crucial on moving from laboratory-scale samples to commercial length.

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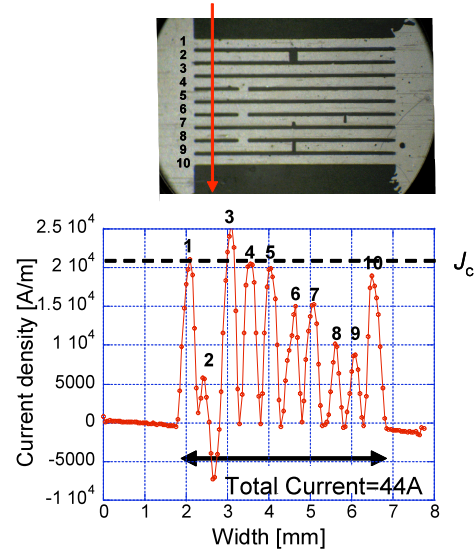


Fig. 4. One-dimensional current profile in the filaments obtained from self-field measurement by Hall-probe microscopy. We can see that shielding current flows in #2 while it can't carry transport current. Reduction of currents in #6, 7 and #8, show good correlation with artificial obstacles and connections in the filaments.

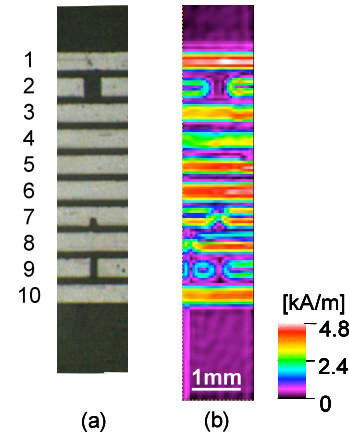


Fig. 5 Magneto scan visualizing local current flow and the influence of obstacles. (a) optical micrograph, and (b) current density.

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