Influence of laser striations on the properties of coated conductors

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Abstract. Due to their high current carrying capability, coated conductors are regarded as the most promising high-temperature superconductor tapes for power applications. However, their high aspect ratio causes too high magnetization losses. To reduce the ac loss, one way is to striate the wide tapes into filaments. We used a picosecond laser for the structuring of (RE)BCO coated conductors. The laser allows to burn 18 µm to 21 µm wide grooves (Ag-cap) with a depth between 0.5 µm to more than 100 µm into the coated conductors, with negligible heat effects at the edges of the structures. Different numbers of filament were structured in Cu- and Ag-cap coated conductors. Patterns with up to 120 parallel filaments in 12 mm wide conductor were made. The critical current and the total ac-magnetization loss were measured as a function of the filament count. With an increasing number of filaments $I_c$ degradation occurs. This current reduction has two contributions, the removed HTS material and current inhomogeneities within the superconductor for instance defects along the tape causing secondary phases. For 120 filaments Ag-cap tapes the hysteresis loss reduction is about two orders of magnitude, as expected. The observation of some remaining filament coupling was investigated.

1. Introduction

Because of their high critical current density $(RE)\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$ ($RE$ is a rare earth, usually Y, Gd or Sm) coated conductors are the most promising high-temperature superconducting tapes for power applications. However, for applications involving windings, like transformers, generators and motors, the AC loss is too large. This is because of the perpendicular field component causing important magnetization AC loss on flat tapes with high aspect ratio [1].

Filamentization of the superconductor reduces the magnetization AC loss and many techniques have been evaluated [2-12]. All these techniques differ in the groove width and depth, the degree of $I_c$ degradation, the amount of coupling losses and the stage of complexity which is directly coupled with the cost. The used picosecond laser provides a reliable one step process with minimized $I_c$ degradation scalable to a reel to reel process. However, these striations are only effective if the filaments are transposed, either by twisting the tape or winding it helicoidally, making composite cables, as it was proven experimentally [10]. This transposition is required because of the coupling currents in the metal connecting the filaments to each other, either at the current leads or along the length of the tape.
But in case of a technical conductor some filament coupling is desirable for a good current sharing and stabilization.

2. Experimental
The structuring was made on 12 mm wide SuperPower tapes with and without Cu stabilization. We used an infrared Nd:YAG-laser with a wavelength of 1030 nm which was pulsed with a frequency of 400 kHz. The pulse duration is less then 10 ps. The maximum power of the laser is 25 W, with maximum pulse energy of 125 µJ. For the structuring of Ag-cap conductors we only used 20 % of the power (5 W) with 10 repetition cycles for each single groove. For Cu-cap conductors we used 50 % of the power (12.5 W) with 50 repetition cycles for each single groove. For the scribing process a combination of a scanner optic with a speed of 90 m/min and a moving table with 22.5 m/min was used. The width of laser grooves is between 18-21 µm for Ag-cap and 37-42 µm for Cu-cap conductors. The resolution of the repeatable track is 0.5 µm.

Samples with up to 120 filaments on 20 cm long tapes were prepared. For the current injection 2.5 cm at both ends of the tapes were not structured. After measuring the U-I curves the ends were cut by laser. These ends were used to investigate the microstructure of the grooves in a scanning electron microscope (SEM). The remaining parts were used for AC loss measurements. For this we used the calibration-free method [13]. In order to understand how the coupling currents flow inside the coated conductor, we measured the transverse resistance between different filaments. All presented measurements were performed at 77 K.

3. Results and Discussion

3.1. Striations
Figure 1 shows top view of samples with 2 µm Ag-cap layer (a-b) and with 20 µm Cu-cap layer (c-d).

![Figure 1. SEM images of striated tapes, a-b) Ag-cap conductor, c-d) Cu-cap conductor with 120 filaments.](image)
For the structuring of Cu-cap conductors in comparison to Ag-cap conductors one has to use higher laser power (12.5 W) and more repetition cycles (50) to go through the Cu. In this case also the hastelloy substrate will be strongly affected by the laser beam, resulting in an inhomogeneous groove edge and bottom. Mainly rows of holes in the hastelloy tape will be seen. For the Ag-cap tapes the structuring is more homogeneous and mainly stops at the hastelloy tape (fig. 1 a)). Nevertheless the $I_c$ measurements together with SEM and FIB investigations indicate that the striation process had negligible heat effects at the edges of the grooves.

3.2. DC measurements
The DC measurements of the critical current as a function of the number of filaments are shown in figure 2.

![Figure 2. Normalized critical current as a function of the number of filaments.](image)

The open symbols in figure 2 represent the expected $I_c$ values solely caused by the loss of superconducting material. Filled symbols represent the measured $I_c$ values. The additional degradation of $I_c$ occurs from statistically distributed inhomogeneities. The influence of inhomogeneities on the current carrying capability increases with decreasing filament width (increasing number of filaments). The Ag-cap sample with 120 filaments has an $I_c$ of 187.5 A, which represents 55% of the critical current of the original tape (342 A). Taking into account that one loses 20 % of superconducting material it reached 68% of the expected value (274 A). The Ag-cap samples with 10 and 20 filaments are basically unaffected by the striation process. They retain 97 % of their current carrying potential. These findings indicate that the striation process does not strongly affect the critical current of the samples. Even the sample with 80 filaments still retains 79 % of its potential. For Cu-cap samples the reduction of $I_c$ is steeper. Here we cut off the edges of the tapes to reduce coupling losses, but this additionally affects and hinders the current rearrangement and percolation, decreasing $I_c$.

3.3. AC measurements and transverse resistance
We measured the losses in dependence of the filament number for different frequencies. The loss reduction with the filament number was slightly less than expected (figure 3), which indicates some degree of coupling between the filaments. We are able to calculate the losses properly by finite-element method (FEM), assuming fully uncoupled filaments [14]. The agreement between simulations
and experiments worsens with increasing number of filament (figure 3). This indicates that the coupling effect is more important for increasing number of filaments.

![Figure 3](image1.png)

**Figure 3.** Magnetization AC losses in dependence on the number of filaments for Ag-cap samples.

We tried to influence the coupling losses by changing the laser parameter, like varying the power and the number of runs. But there are no clear dependencies. Additionally we oxidized the Ag-cap samples after the standard laser process at 500°C for 1 h in pure oxygen to see if the resistance of the groove increases [12]. With this process the groove resistance (measured with four point method) increases about two orders of magnitude up to 650 mΩ compared to the grooves after the standard laser process with 3 mΩ. In figure 4 the losses normalized by the square of the applied field amplitude for standard laser processed tapes and additional oxidized tapes at 130 Hz are shown.

![Figure 4](image2.png)

**Figure 4.** AC losses normalized by the square of the applied field amplitude for standard and oxidized Ag-cap tapes. Blue line: FEM simulation for totally uncoupled filaments.
In figure 4 it is clearly visible that the oxidation treatment is a quite effective tool to reduce the coupling loss by increasing transverse resistivity. For the sample with 10 filaments nearly no effect of the oxidation is seen, because even in the standard sample the coupling loss is very low. With increasing number of filaments the loss reduction increases. For the 120-filament tape a large loss reduction occurs. At 130 Hz the standard 120-filament tape is almost flat. Because the coupling loss is proportional to $\text{Ba}^2$, the loss of a fully coupled tape should be constant in the whole range of the field amplitude. The oxidized tape with 120 filaments is in between the two extreme cases, the FEM simulation with no coupling and the standard 120-filament tape fully coupled. In the case of Cu-cap samples one frequency was measured. The loss is about 6 times higher than in Ag-cap samples. Cutting off the Cu edges from the samples reduces the loss about a factor of 2.

4. Summary
Ag-cap and Cu-cap tapes from SuperPower were structured with an Nd:YAG picosecond laser system. We made up to 120 filaments in 12 mm wide tapes. Because of using higher power for the Cu-cap tapes, the substrate tape is also affected resulting in row of holes inside the hastelloy tape. Nevertheless in both Ag- and Cu-cap tapes the laser did not strongly affect the material beneath the edges of the grooves. DC measurements showed a decreasing $I_c$ with increasing filament numbers. This is caused by the loss of superconducting material and by statistically distributed inhomogeneities affecting the rearrangement and percolation of the current. The striated tapes show some filament coupling, which is more important as the number of filaments increases. The groove resistance could be increased of about two orders of magnitude during a heat treatment at 500°C in pure oxygen for Ag-cap samples. The AC loss measurements of these samples indicate a clear decrease of the coupling loss, especially for tapes with high filament numbers.

References
[1] Brandt E H and Indenbom M 1993 Physical Review B 48 12893–906
[2] Sumption M D, Collings E W and Barnes P N 2005 Supercond. Sci. Technol. 18 122
[3] Duckworth R C, List F A, Paranthaman M P, Rupich M W, Zhang W, Xie Y Y and Selvamanickam V 2007 Physica C 463-465 755
[4] Majkic G, Kesgin I, Zhang Y, Qiao Y, Schmidt R and Selvamanickam V 2011 IEEE Trans. Appl. Supercond. 21 3297
[5] Marchevsky M, Zhang E, Xie Y, Selvamanickam V and Ganesan P G 2009 IEEE Trans. Appl. Supercond. 19 3094
[6] Suzuki K, Matsuda J, Yoshizumi M, Izumi T, Shiohara Y, Iwakuma M, Ibi A, Miyata S and Yamada Y 2007 Supercond. Sci. Technol. 20 822
[7] Tsukamoto O and Ciszek M 2007 Supercond. Sci. Technol. 20 974
[8] Lee J K, Kim W S, Park C, Byun S, Han B W, Lee S, Park S and Choi K 2009 Physica C 469 1432
[9] Terzieva S, Vojenčík M, Grilli F, Nast R, Šouc J, Goldacker W, Jung A, Kudymow A and Kling A 2011 Supercond. Sci. Technol. 24 045001
[10] Šouc J, Gömöry F, Kováč J, Nast R, Jung A, Vojenčík M, Grilli F and Goldacker W 2013 Supercond. Sci. Technol. 26 075020
[11] Koperá L, Šmatko V, Prusseit W, Polášek M, Semerad R, Štrbík V and Šouc J 2008 Physica C 468 2351
[12] Kesgin I, Majkic G and Selvamanickam V 2013 Physica C 486 43
[13] Šouč J, Gömőry F and Vojenčík M 2005 Supercond. Sci. Technol. 18 592
[14] Brambilla R, Grilli F and Martini L 2007 Supercond. Sci. Technol. 20 16