# Contactless measurements of local transport characteristics of coated conductors under the bending strain

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**Abstract.** The influences of bending strain on the critical current density $J_c$ in coated conductor (CC) tapes were investigated at 77 K by contactless method based on scanning Hall probe magnetometry (SHPM). In order to clarify the reasons of variations in critical current for different bending radius we carried out local studies of critical currents in CC tapes before and after bending strain. By using SHPM we defined two-dimensional maps of critical current distribution at various bending radiuses. It was demonstrated that the superconducting layer in CC tape cracked at critical bending radius into periodical regions with unchanged and decreased transport properties. Appearance of local cracks with reduced value of the critical current leads to degradation of the critical current of the whole tape. It is found that the both critical bending radius and kind of tape cracking depend on the type of metallic substrates. The results of contactless studies are in good agreement with direct transport measurements.

## 1. Introduction

Advances in the fabrication processes of coated conductor tapes based on high temperature superconductors (HTSC) have lead to real possibility to use CC tapes in electrical application such as superconducting electric power cables, motors, wind generators, magnets, etc. During fabrication and practical operation of superconducting devices the coated conductor experiences various stresses. One of them is the bending stress during the winding of coils. So it is necessary to investigate the mechanical bending strain property of $YB_2Cu_3O_{7-x}$ (YBCO)-coated conductors with high $J_c$. For YBCO CC tapes, some electro-mechanical properties have been investigated by various research groups which include tensile, transverse compressive and bending strain dependence of the $J_c$ [1–8]. Under bending deformation, when a strain was over 0.5%, cracking was observed using a scanning electron microscope (SEM). The generation of crack appeared to be the primary reason for $J_c$ degradation [2,6]. In the above papers the critical current was measured by transport methods, and the observation of cracks by using SEM was carried out after chemical removing of the protective layers that could result in loss of integrity of HTSC composite. It should also be noted that the transport methods do not reflect the local distribution of critical current and do not allow to observe the dynamics of appearance of local areas with reduced critical current.

In this report we present new results of visualization of critical current distribution in CC tapes under bending deformation. We demonstrate that the superconducting layer in CC tape cracks at some bending radius into periodical regions with unchanged and decreased critical current.

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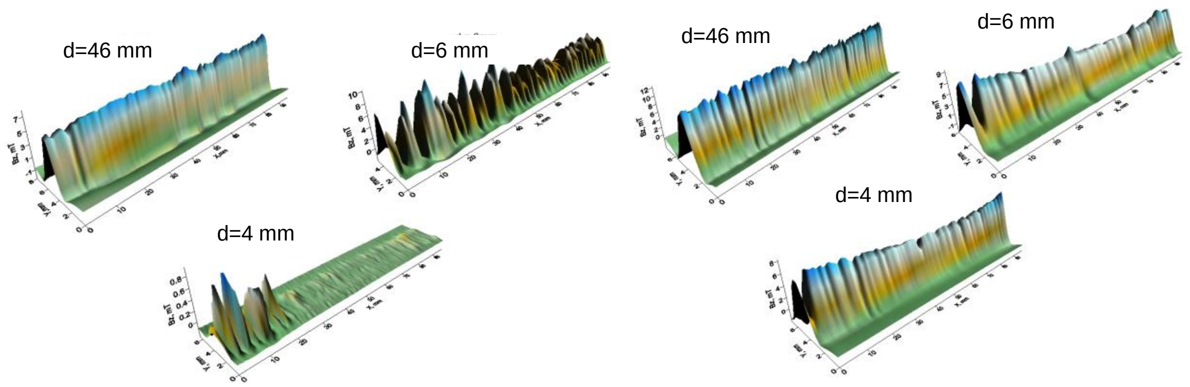
## 2. Materials and methods

For studies we selected two types of tapes produced by SuperPower (SP) and American Superconductor (AMSC), which differ in the substrate and internal architecture. The tapes were wound on cylinder with diameter *d* , cooled, warmed and then the measurements of trapped magnetic flux were done at *T*= 77 K. Whole procedure was repeated for several cylinders with diameters *d* from 50 mm to 4 mm. For measurements of trapped magnetic field we used home-made SHPM equipment. Two-dimensional distributions of the critical current as well as the distribution of the longitudinal and transverse $J_c$ components were obtained from the local magnetic induction data according to algorithm described in Ref. [9, 10]. The studies were performed for two variants of tapes winding: the superconducting layer was inside or outside the bend of tapes. The first case corresponds to compression strain in superconducting layer, the second one – to tensile strain.

## 3. Results and discussion

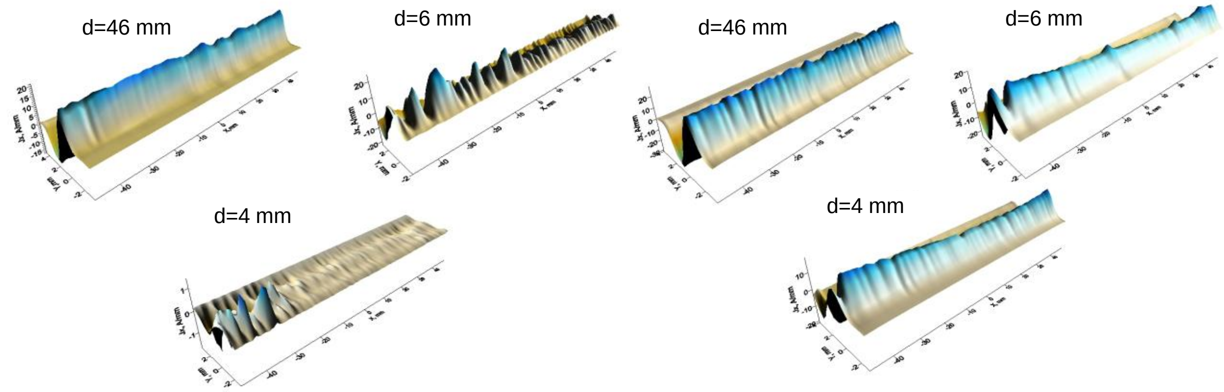
Figure 1 shows the two-dimensional distributions of the trapped magnetic induction $B_z(x,y)$ for the cases of tensile and bending strain. In both cases the surfaces $B_z(x,y)$ are given for the three bending diameters $d$ = 46 mm, 6 mm and 4 mm. From these figures one can see that for large values $d$= 46 mm distribution $B_z(x,y)$ are sufficiently homogeneous. Distributions $B_z(x,y)$ are approximately the same for the cases of tension and compression. A sharp discontinuity $B_z(x,y)$ is observed at $d$ = 6 mm for the case of tensile bending strain. This discontinuity $B_z(x,y)$ indicates that there is a separation of the sample to the superconducting and non-superconducting regions. Perhaps it means the appearance of mechanical cracks in HTSC layer like it was shown in [2, 6]. A further decrease in diameter down to 4 mm leads to disappear of superconductivity almost completely. In the case of compressive bending strain a different scenario takes place. At $d$ = 6 mm and $d$ = 4 mm the superconducting layer does not crack, and the distributions $B_z(x,y)$ are sufficiently uniform. However, decrease in diameter $d$ leads to gradual reduce of trapped flux. From the matrix of values $B_z(x,y)$ we calculated spatial distribution of longitudinal $J_x(x,y)$ and transverse $J_y(x,y)$ components of the critical current density. Component $J_x(x,y)$ formally characterizes the transport critical current as it is directed along the tape, while $J_y(x, y)$ reflects the presence of current flow heterogeneity, which causes a deviation of the current lines along the direction of the tape. Figure 2 shows the longitudinal components $J_x(x,y)$ obtained from $B_z(x,y)$ data. In the case of tension the appearance of regions with sharply reduced $J_c$ for $d$ = 6 mm and a full $J_c$ loss at $d$ = 4 mm can be clearly seen. Figure 3 shows the dependencies of the maximum and minimum critical current on bending diameters $d$ obtained from values $J_x(x,y)$ for different $d$.

To compare the different types of tapes (see Figure 4) the experimental data were reconstructed as the dependence of the critical current on bending strain $\varepsilon$, which was defined as $\varepsilon = t / (2R + t) \times 100\%$, where t is the thickness of tape and $R$ is bend radius.




(a) (b)

**Figure 1**. Experimental surfaces of the remanent magnetization distribution with various bending diameters $d$=46, 6 and 4 mm. (a) Sample No.1 (tensile bending strain), (b) Sample No.2 (compressive bending strain). The coordinate axes: abscissa – ($X$, mm); ordinate – ($Y$, mm); applicata – ($B_z$, mT).




(a) (b)

**Figure 2.** Distribution of shielding currents along the tapes with various bending diameters *d*=46, 6 and 4 mm. (a) Sample No.1 (tensile bending strain), (b) Sample No.2 (compressive bending strain). The coordinate axes: abscissa – (*X*, mm); ordinate – (*Y*, mm); applicata – ($J_x$, A/mm).

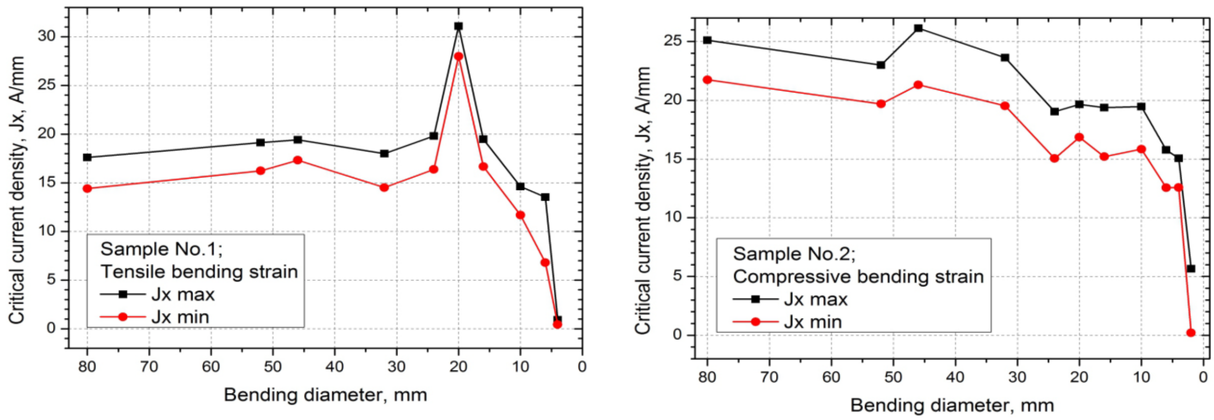



**Figure 3.** The dependence of the maximum and minimum values of the longitudinal component of the critical current density on the bending diameter for tensile bending strain (left) and compressive bending strain (right).

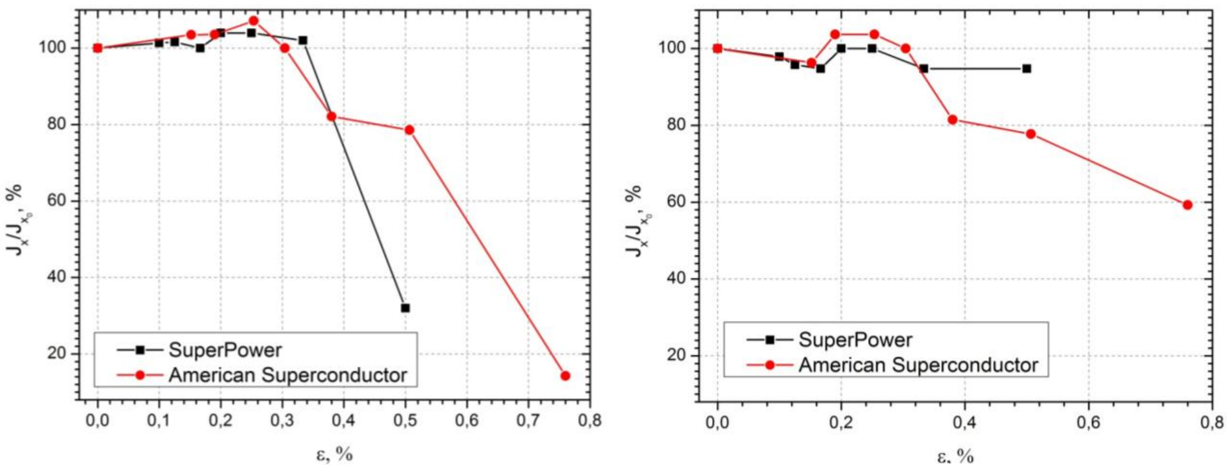



**Figure 4.** The dependence of normalized critical current density on the bending strain for SP and AMSC tapes. Left - tensile bending strain, right - compressive bending strain.

Calculations of bending strain $\varepsilon$ show that the superconducting layer in the AMSC tapes is subjected to the high mechanical stresses compared to SP tapes for the same radius of curvature due to position of the neutral axis of strain through the thickness of the substrate. SP samples do not experience significant changes in the critical current of up to 0.5% strain, then in the case of stretching the critical current drops sharply by 70%. The strains 0.5% corresponds to $d$=10 mm.

Degradation of the critical current of AMSC tapes clearly observed from $\varepsilon$=0.38% strain, which corresponds to the bending diameter 25 mm. At 0.5% strain ($d$=15 mm) $J_c$ is reduced in 20%. When the deformations reach 0.76% (10 mm) $J_c$ decreases in 40% for the case of compressive strain and in 85% for the case of tensile strain. The difference in the data for different types of tapes is related to the difference of mechanical properties and structural features of substrates.

## 4. Conclusion

The influence of bending strain on critical current density in YBCO coated conductors was investigated by local magnetic method based on scanning Hall probe techniques. The obtained results are summarized as follows:

(1) In the region of small deformation (i.e. small strain) HTSC layer deforms elastically and critical current density does not change. At strain 0.3% – 0.5% plastic flow of the substrate materials begins that leads to degradation of HTSC critical current.

(2) Behavior of the critical current is different for the cases of the tensile or compressive bending strain. Namely, for the tensile strain samples crack at bending diameter 10 mm while in the second case no occurrence of cracks is observed down to $d$=4 mm.

(3) The behavior of the critical current density in the bending strain is different for SP and AMSC tapes. Plastic flow of AMSC tapes begin at lower values of strain, but cracking of HTS layer occurs first in the SP samples. The observed differences may be due to several reasons: different positions HTS layer relative to the neutral axis, the different mechanical properties of the substrate materials, various mechanisms of stress for these materials.

It should also be noted that we observed a decrease in $J_c$ after eight weeks at a constant exposure to bending strain. Value reduction ranged from 8% to 25% for different diameters of the bend. This phenomenon may be due to materials creep.

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## References

[1] Cheggour N, Ekin J W, Clickner C C, Verebelyi D T, Thieme C L H, Feenstra R, Goyal A and Paranthaman M 2003 *IEEE Trans. Appl. Supercond.* **13** 3530
[2] Park C, Norton D P, Budai J D, Christen D K, Verebelyi D, Feenstra R, Lee D F, Goyal A, Kroeger D M and Paranthaman M 1998 *Appl. Phys. Lett.* **73** 1904
[3] Shin H S, Kim K H, Dizon J R C, Kim T H, Ko R K and Oh S 2005 *Supercond. Sci.Technol.* **18** S364
[4] Sugano M, Osamura K, Prusseit W, Semerad R, Itoh K and Kiyoshi T 2005 *Supercond. Sci. Technol.* **18** 369
[5] Cheggour N, Ekin J W, Thieme C L H, Xie Y Y, Selvamanickam V and Feenstra V 2005 *Supercond. Sci. Technol.* **18** S319
[6] Sutoh Y, Kakimoto K, Kaneko N, Iijima Y and Saitoh T 2005 *Physica C* **421–430** 933
[7] Shin H S, Dedicatoria M J, Dizon J R C, Ha H S and Oh S S 2009 *Physica C* **469** 1467
[8] Sugano M, Machiya S, Sato M, Koganezawa T, Shikimachi K, Hirano N and Nagaya S 2011 *Supercond. Sci. Technol.* **24** 075019
[9] Pokrovskiy S V, Rudnev I A and Podlivaev A I 2009 *J. Phys. Conf. Ser.* **150** 052211
[10] Rudnev I A, Pokrovskiy S V and Podlivaev A I 2012 *IEEE Trans. Appl. Supercond.* **22** 9001304