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ANALYSIS OF THE BENDING STRAIN INFLUENCE ON THE CURRENT--VOLTAGE CHARACTERISTICS OF HTC SUPERCONDUCTING TAPES

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Abstract. *Analysis of the influence of the bending strain on the electric properties of the HTc superconducting tapes is presented. The results of experimental investigations in liquid nitrogen temperature of the current-voltage characteristics and critical current of Bi-based tape are given for various bending strain values. Theoretical model of obtained dependences is proposed, while results of numerical calculations are in qualitative agreement with experimental data.*

Keywords:bending strain, current-voltage characteristics, HTc superconductors, capturing effects

ANALIZA WPŁYWU ODKSZTAŁCENIA PRZY ZGINANIU NA CHARAKTERYSTYKI PRĄDOWO-NAPIĘCIOWE WYSOKOTEMPERATUROWYCH TAŚM NADPRZEWODNIKOWYCH

Streszczenie. *Przeprowadzono analizę wpływu odkształcenia przy zginaniu na elektryczne własności wysokotemperaturowych taśm nadprzewodnikowych. Zaprezentowano wyniki badań doświadczalnych w temperaturze ciekłego azotu charakterystyk prądowo-napięciowych i prądu krytycznego taśm nadprzewodnikowych opartych na bizmucie, w funkcji wartości odkształcenia przy zginaniu. Teoretyczny model otrzymanych zależności został zaproponowany, którego numeryczne rezultaty są w dobrej jakościowej zgodności z wynikami doświadczalnymi.*

Słowa kluczowe: odkształcenie przy zginaniu, charakterystyki prądowo-napięciowe, nadprzewodniki wysokotemperaturowe, efekty zakotwiczenia

Introduction

Continuous growth of the critical temperature of the HTc superconductors bringing now the value of 203 K in sulfur hydride system [1] leads to the rapid increase of the interest in the applications of these materials in electric engineering. However we should remember that applications of them is dependent on the technical parameters of the HTc superconducting tapes, which are influenced by the subtle structure of ceramic superconductors, expressed for instance in sensitivity of their properties to bending strain. In paper is given electromagnetic analysis of the influence of this effect on the current-voltage characteristics of the HTc tapes. This model deals to both, the first and second generation HTc tapes, in which appear superconducting elements in the form of thin filaments or superconducting films stabilized by silver sheath. This topic is further important from scientific and technical point of view, investigated recently among other in [2, 4, 6], in which papers are presented changes of the electric properties of BSCCO, DI-BSCCO and YBCO tapes subjected to strain.

1. Experimental data

For verifying proposed in the next chapter theoretical model of the creation in the bending strain process of the micro-cracks in HTc superconducting tapes and influence of this effect on the electric properties of tapes, the experimental measurements have been performed. Four contacts method has been used for measuring current-voltage characteristics. Superconducting tape has been folded in room temperature up to required value of the bending strain, on the especial form and then this setup was cooled in the cryostat filled with liquid nitrogen. Direct electric current flowed through the high temperature superconducting tape and current-voltage characteristics have been measured using sensitive micro-voltmeter. The results of measurements current-voltage characteristics as the function of the bending strain are presented in the Fig. 1. Dots indicate the experimental data, while solid line is approximation by power function. The bending strain is defined according to the relation:

$$e\,(\%) = 100\, t/R \tag{1}$$

where e is value of the bending strain in percent, t half-thickness of the tape, R bending radius. Received on the base of these measurements, the influence of the bending strain on the critical current of the HTc superconducting tape is given in Fig. 2. It is seen, according to the Fig. 2 that for low values of the bending strain occurs reversible, elastic process, which does not influence significantly the critical current, while for higher bending strains there appear not reversible, destructive mechanical processes, creating micro-cracks, which lead to the decrease of the critical current. In the present case this decrease of the critical current with bending strain has been described by the linear approximation, fitted to the experimental data presented in Fig. 2.

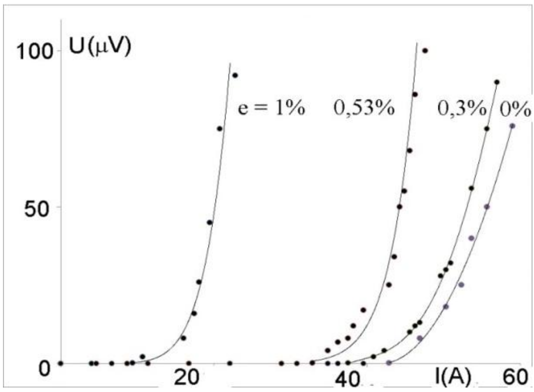

Fig. 1. Experimental current-voltage characteristics at liquid nitrogen temperature of high temperature superconducting BSCCO tape, as a function of the bending strain parameter e

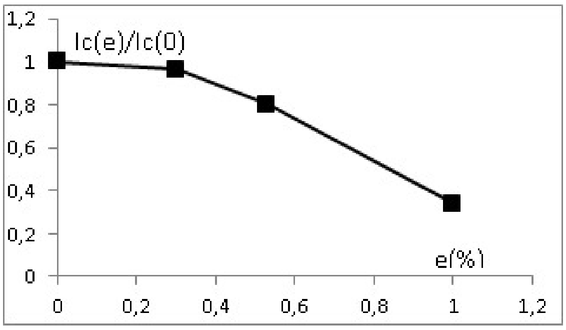

Fig. 2. The experimental (squares) and linearly approximated (solid line) dependence of the critical current of the HTc superconducting tape on the bending strain at liquid nitrogen temperature

In this paper it has been taken into account too in details geometrical effect indicating, that it will be slightly different bending strain value acting on the individual filament in the first generation tape or film in second generation, in comparison to bending strain applied to total superconducting tape. Schematically such bending strain geometrical effect is shown in Fig. 3 in simplified case in which individual filament is covered by the silver sheath. R_{out} is external radius of the tape during bending, R_{sh} radius then of the sheath, while R_{fil} radius of bent filamentin 1G or film in 2G tape. Taking into account the differences between geometrical lengths of these parameters we receive slightly different values of the applied to the superconducting tape bending strain e and bending strain acting on the filament e_{filg}. This effect is mathematically described by the following relations:

$$e = 100\cdot(R_{out} - R_{fil})/(R_{out} + R_{fil}) \quad (2)$$

$$e_{filg} = 100\cdot(R_{sh} - R_{fil})/(R_{sh} + R_{fil}) \quad (3)$$

The calculated on this base relations between the bending strain parameters e and e_{filg} for various filaments thicknesses, in the relative units are given in the Fig. 4.These results indicate on the approximately linear dependence between above both parameters, it is $e_{filg} = \gamma e$, with γcoefficient of proportionality smaller than 1, for the case shown in the Fig. 4.

2. Theoretical analysis

Theoretical model has been elaborated next describing the influence of the bending strain on the electromagnetic properties: current-voltage characteristics and critical current I_C of HTc superconducting tapes, explaining measured dependences shown in Figs. 1-2.

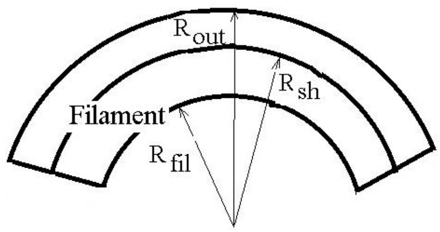

Fig. 3. Simplified view of the filament surrounded by the silver sheath in the superconducting tape at the bending strain process

In present approach analogously as in[3], it has been in details considered the subtle structure of the superconducting tape, composed from thin filaments or film immersed in silver matrix. Such theoretical analysis has important technical meaning because the effect of the bending strain appears in various applications of the superconducting tapes, especially occurs during winding process of the superconducting electromagnets. It concerns also the superconducting wires, in which filaments are usually twisted, while formed from them cables [5] can be also folded. Shown in Fig. 2 the dependence of the critical current on the bending strain e, describes the rupture probability function $G(e)$, which has been approximated here according to data of Fig. 2 through the linear relation:

$$G(e) = 1 - I_C(e)/I_C(0) = 0.96(e - e_c) \quad (4)$$

for $e>e_c = 0.3\%$. According to Fig. 2, for bending strain smaller than critical one e_c, appears in superconducting tape an elastic, reversible region, in which micro-cracks do not arise, therefore $G(e < e_c) = 0$. For higher bending strains it begins then the creation of the micro-cracks in the filaments or films, due to the breaking forces acting on the total tape and immersed in the silver matrix filaments. This effect will influence the transport of the electric current and critical current value, as shows Fig. 2. The elastic properties of silver matrix lead then to the reduction of the strain in filaments in comparison to the total applied strain. The regular ordering of the micro-cracks in the filaments allows to treat them as long line of deformed elements interlaced with the long line, which contains undeformed filaments. In resistive state it appears therefore analogy to the electrical long line of resistors as is shown in Fig. 5. R_1 in this figure, is the resistance on unit length of the undeformed filament in the resistive state, while R_2 is the resistance of the matrix and R_c is resistance on unit length of the deformed tape, by presence of micro-cracks.

Basing on the Fig. 5 it is easily to find then the simple mathematical relations describing variation with the depth of the voltage and current in such long line taking into account the leakage of the current through the normal matrix and voltage drop along the long line. For deformed by the existence of the micro-cracks long line the appropriate relations describing current and voltage variation $dV/dx = -R_cI$ and $dI/dx = -V/R_2$ lead to the following dependence:

$$\frac{\partial^2 I}{\partial x^2} = \frac{R_c}{R_2} I \quad (5)$$

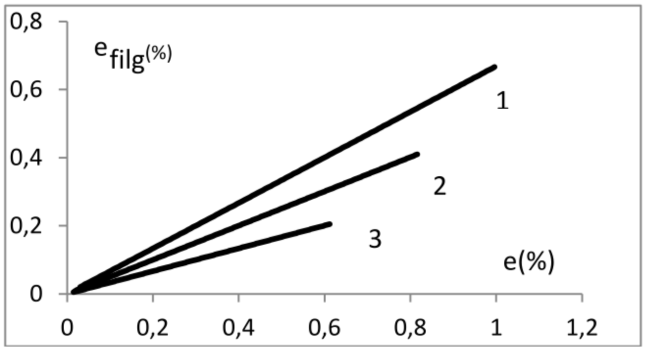

Fig. 4. Relation, following from the geometrical factor, between applied to the tape bending strain e and bending strain acting onthe filament e_{filg} calculated for various values of the filament thickness in relative units $z = (R_{out} - R_{sh})/(R_{sh} - R_{fil})$: (1) z = 0.5; (2) z = 1.0; (3)z = 2.0.

Decreasing with depth inside long line the solution of Eq. 5, describing the leakage of the current to the sheath, has been found in the exponential form:

$$I(x) = I(0)\cdot\exp\left(-\sqrt{\frac{R_c}{R_2}}x\right) \quad (6)$$

and then voltage variation has been determined:

$$V(x) = I(0)\sqrt{R_cR_2}\cdot\exp\left(-\sqrt{\frac{R_c}{R_2}}x\right) \quad (7)$$

while effective resistance per unit length of this deformed tape is:

$$R_{effd} = \sqrt{R_c\cdot R_2} \quad (8)$$

Analogously the expression for the effective resistance in resistive state per unit length of the tape, containing undeformed regions joined in parallel to the sheath, is:

$$R_{effu} = \sqrt{R_1\cdot R_2} \quad (9)$$

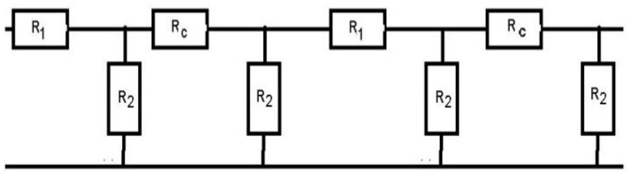

Fig. 5. Simulation of the HTc superconducting multifilamentary tape with ordered micro-cracks as the long line of resistors R_C and R_1

Similar picture has been applied next for the description of the elastic properties of the HTc superconducting tape, which determine then the micro-crack creation under bending strain process. It has been considered the relations between the elasticity spring constant k of the HTc superconducting tape and bending strain e acting on the total tape, with spring constant k_{fila} and bending strain e_{fila} in the filaments [3]. These last values due to amortizing effects of the silver sheath, expressed by the parameters k_{sh} and e_{sh} should be smaller. Additionally total bending strain acting on the filaments e_{fil} will be modified in the respect to the applied bending strain due to the geometrical reasons, finite thickness and curvature of the bended filaments, as it was described in previous chapter.

Relations between these parameters describing the elasticity properties of the deformed multifilamentary superconducting tape will be described therefore by the similar picture as in the case of the resistive long line model shown in the Fig. 5, where k_{fil} corresponds toR_1, while k_{sh} to R_2. Then as it was shown in [3] new relations arise joining the applied bending strain parameters e and acting on the filament e_{fila} with appropriate resistances in long line model approach $e/e_{fila} = R_1/R_{eff} = k_{fil}/k_{eff}$, where R_{eff} is the effective resistance on unit length of the long line shown in the Fig. 5. We should additionally introduce the condition connected with the fact that while the micro-cracks appear in filament then stress force will be directed onto the sheath, which elasticity properties are suppressed therefore, so elasticity parameter k_{sh} will decrease with enhancement of rupture probability $G(e)$. In the present paper such relation has been approximated by formula:

$$k_{sh} \approx k_{fila} \frac{1-G(e)}{1+G(e)} \tag{10}$$

Above considerations allow to determine then the bending strain acting on the filaments e_{fila}, the part connected with elasticity properties of the multifilamentary tape, as the function of the applied strain e:

$$e \approx e_{fila} \cdot \sqrt{\frac{1+G(e)}{1-G(e)}} \tag{11}$$

Eq. 11 is useful for evaluation next the length of the micro-cracks in the filament, which average value was assumed, to be determined by the difference between the applied e and acting on the filament total bending strain e_{fil}

$$e_{fil} = \gamma \cdot e \cdot e_{fila} \tag{12}$$

and is described according to the following relation:

$$l_e = \gamma\left(e - e_{fil}\right) \frac{50\left(1+\frac{R_{out}-R_{sh}}{R_{sh}-R_{fil}}\right)+\frac{R_{out}-R_{sh}}{R_{sh}-R_{fil}}-\frac{1}{2}}{50\left(1+\frac{R_{out}-R_{sh}}{R_{sh}-R_{fil}}\right)+\frac{R_{out}-R_{sh}}{R_{sh}-R_{fil}}+\frac{1}{2}} \tag{13}$$

Here parameter l_e is the relative length of the microcracks in the deformed regions in the unit length of the tape, while parameters R_{sh},R_{out},R_{fil} describe the bending radius of sheath, radius of the total tape and bending radius of the filament as it was explained in the Fig. 3.The average depth of the micro-crack g is then given by the product

$$g = (R_{sh} - R_{fil}) \cdot G(e) \tag{14}$$

according to the notation presented in the Fig. 3. Above equations indicate on the importance of the proper choice of the rupture probability function for determining the electric and elastic properties of the HTc superconducting tapes.

In the present paper it has been considered therefore, beside linear with bending strain form of function $G(e)$ described by Eq. 4,fractional and exponential approximations, which also correspond well to data shown in Fig. 2.

Results of calculations of the dependence of acting on filament elastic part of the bending strain as the function of applied bending strain are shown in Fig. 6 for various shapes of the $G(e)$ functions and indicate on the good agreement obtained between each of these approximations.

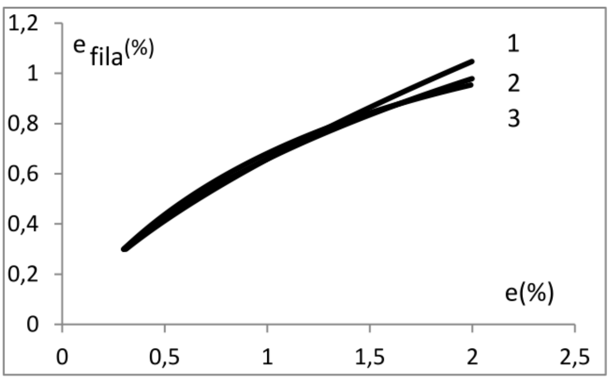

Fig. 6. Calculated dependence of the elastic part of the bending strain acting on HTc superconducting filament e_{fila} on the applied bending strain e for: (1) fractional, (2) exponential and (3) linear shape of the rupture probability function G(e)

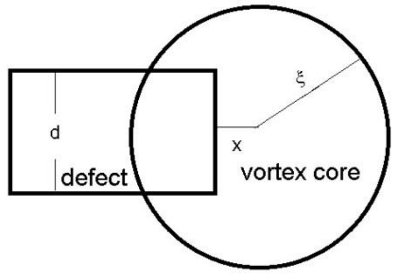

Fig. 7. Schematic view of the pancake shape magnetic vortex core interaction with the nano-defect of size d

Now we can pass therefore to the determination of the current-voltage characteristics of bended HTc superconducting tape. Effective resistance R_{eff} of the unit length of such tape is then the amount of these components given by Eqs. 8-9, with appropriate weight factor describing the relative lengths of these both regions in treated as long line superconducting tape, as it was explained previously:

$$R_{eff} = \sqrt{R_1(1-l_e)R_2} + \sqrt{R_c \cdot l_e \cdot R_2} \tag{15}$$

Existence of these two types of the regions denotes that although the same current flows through the superconducting tape others are current-voltage characteristics in both these regions: deformed and undeformed by the existence of the micro-cracks, because current density is different then. This effect concerns resistances R_1 and R_c connected with the undeformed section of the tape and the deformed one, respectively, as it follows from the relations:

$$R_1 = E\left(\frac{I}{S}\right)/I \,, R_c = E\left(\frac{I}{S(1-G)}\right)/I \tag{16}$$

$E(j = I/S)$ in Eq. 16 is just the current-voltage characteristic for the unit length of the superconducting tape, of the cross-section of tape S, while I is transport electric current. Right part of Eq. 16 gives the current-voltage characteristic divided on current for tape with microcrack, so with smaller cross-section, which is just described by the product S(1-G).

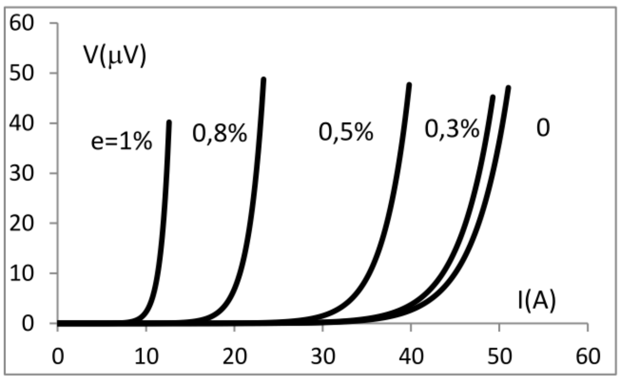

Fig. 8. Theoretically calculated influence of the bending strain e on the current-voltage characteristics of the HTc superconducting multifilamentary tape with ordered micro-cracks

As it follows from this equation16 very important function plays in the present considerations the shape of the current-voltage characteristics function *E(j)*. In the present paper theoretical model of the current-voltage characteristics has been applied, based on flux creep equation, describing flux creep forward and backward processes given by Eq. 17:

$$E = -B\omega\, a\left(e^{\frac{-\Delta U(0)(1+i)}{k_B T}} - e^{\frac{-\Delta U(i)}{k_B T}}\right) \tag{17}$$

Here $i = j/j_c$ is reduced to critical transport current density,ω is flux creep process frequency, a average distance between nano-defects acting as pinning centers, k_B means Boltzmann's constant, T temperature. Eq. 17 describes the current-voltage characteristics, which is required for solving relation 16 in the function of potential barrier for flux creep process $\Delta(i)$.

For determining the shape of this barrier detailed analysis has been performed of the capturing interaction between the pancake vortices specific for HTc multilayered superconductors with defects of rectangular shape, which correspond to micro-cracks. The geometrical scheme of such interaction shown in Fig. 7 presents the vortex core pinned on the normal state defect of the width *d* on the length x against the initial position, for which x = 0 and vortex is then half captured onto the depth of the coherence length ξ. Various initial captured vortex positions have been considered in this analysis too. This model leads to following expression 18 for the potential barrier ΔU in the function of reduced current $i = I/I_c$ and nano-defect size *d* reduced to the coherence length ξ. H_c is critical magnetic field, *l* thickness of superconducting layer.

$$\Delta U(i) = \frac{\mu_0 H_c^2}{2} l \xi^2 \left(-\arcsin(i) + \arcsin\left(\frac{d}{2\xi}\right) + \frac{d}{2\xi}\sqrt{1-\left(\frac{d}{2\xi}\right)^2} - i\sqrt{1-i^2} \right) \quad (18)$$

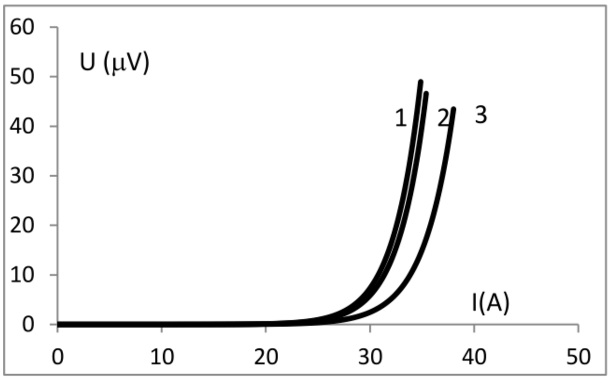

Fig. 9. Influence of the shape of the rupture probability function G(e) on the current-voltage characteristics U(I) of the HTc superconducting tape with ordered micro-cracks for e = 0.5%, B = 0.05 T at: (1) fractional approximation (2) exponential approximation (3) linear approximation

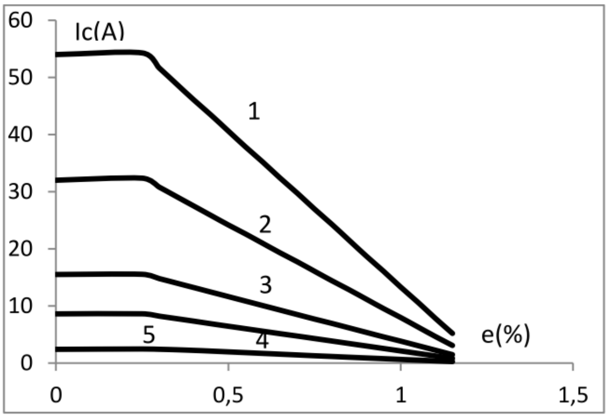

Fig. 10. Dependence of the critical current on the bending strain versus the coherence length: (1) ξ = 3 nm, (2) ξ = 3.57 nm,(3)ξ = 4 nm, (4)ξ = 5 nm, (5) ξ = 6 nm

Final results of calculations influence of bending strain on current-voltage characteristics are presented in Fig. 8for linear shape of the rupture probability function *G(e).*Results shown here well correspond qualitatively to the experimental data given in Fig. 1, which conclusion confirms validity of the presented model. On the importance of the rupture probability function *G(e)*at the critical current analysis indicates Fig. 9, in which is presented theoretically predicted influence of the form of this function *G(e)*: linear, fractional or exponential on the current-voltage characteristics of the HTc superconducting multifilamentary tape with regularly ordered micro-cracks. In Fig 10 are given the results of calculations influence of the coherence length on the dependence of the critical current versus the bending strain magnitude.

Realized work indicates on the importance of problem of deformation arising especially in the bending strain process, which influences the electrical properties of the HTc superconducting tapes, first and second generation, such as current-voltage characteristics and their critical currents.

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