MAGNETIZATION REVERSAL OF A TYPE-II SUPERCONDUCTOR THIN DISK UNDER THE ACTION OF A CONSTANT MAGNETIC FIELD

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The applicability of relations obtained by Clem and Sanchez for the ac magnetic susceptibility of type-II superconductor thin films to the case where an additional constant magnetic field is applied perpendicularly to the film has been analyzed in the framework of the critical state model. The issues concerning the sample "memory" and the influence of the magnetic field change prehistory on the current sample state have been discussed. It has been shown that the *ac* component of the magnetic moment and, hence, the amplitudes of *ac* magnetic susceptibility harmonics are established within one period of the ac magnetic field irrespective of the field prehistory.

1. Introduction

One of the techniques aimed at determining the critical current density in high-temperature superconductor thin films is the noncontact measurement of their magnetic susceptibility in an alternating field (the *ac* magnetic susceptibility). It is based on the magnetization reversal model for a superconductor of the second kind which was theoretically substantiated in works [1–3]. In work [3], Clem and Sanchez obtained a relation for the *ac* magnetic susceptibility of a thin disk provided that only an *ac* magnetic field acts on the disk (the CS-model). However, the further experimental researches of the critical current density in thin superconductor films allowed the scope of the CS relation to be extended upon the results of measurements in a *dc* magnetic field as well [4–9]. In the literature, there are only collateral (indirect) verifications that such an extension is valid. The authors of work [4] believe that the imposed constant field does not change the expression for *ac* magnetic susceptibility obtained in work [3], if the critical current density weakly depends on the magnetic field. A similar conclusion can be drawn from Brandt's remark [10] that, in the case of a periodic field with slowly growing amplitude, a Bean superconductor (i.e. a superconductor described in the framework of the critical state model developed by Bean [11]) "reminds" only the last cycle of magnetization reversal. The presented speculations may intuitively seem plausible; however, their validity is not evident *a priori*, and their more rigorous substantiation is required. The absence of such a substantiation in the literature forces experimenters to carry out additional checks of the CS-model applicability under that or another experimental condition [4, 5, 7].

For ordinary magnets, the amplitude of local magnetization in a magnetic field is almost uniform over the specimen volume in the case where the specimen shape is an ellipsoid of rotation; in this case, the magnetization is a characteristic of the medium (substance). The hysteresis phenomenon consists in an ambiguity of the local magnetization dependence on the external field. For a superconductor of the second kind in a magnetic field, primary is the spatial distribution of the screening current density on a macroscopic scale (in reality, on the specimen-size scale, whatever the specimen shape). The current distribution is governed, in particular, by the entry/exit of Abrikosov vortices; and the magnetic moment and the volume-averaged magnetization are integral characteristics of the specimen, being the derivatives of the current distribution. As a consequence, the hysteresis dependence of superconductor magnetic characteristics on the external magnetic field turns out to be a complicated indirect one. This circumstance makes an answer to the question on the specimen "memory", i.e. on the influence of a sequence of external conditions ("prehistory") imposed on the specimen on its state, nonevident *a priori.* This prehistory includes variations of the applied magnetic field, by starting from the moment, when the specimen is in the ZFC (zero field cooling) state, i.e. in the state obtained by cooling down the specimen in the zero external magnetic field from the temperature $T > T_c$, where T_c is the critical temperature of transition into the superconducting state. The key parameters of the CS model are the external magnetic field and the critical current density, the latter being a function of the temperature. Therefore, the "prehistory" also includes the sequence of temperature regimes applied to the specimen after the magnetic field having been imposed.

In this context, Brandt's statement given above is valid only partly, and an additional explanation is required. For instance, if the specimen state – i.e. the spatial distributions of the current density and the magnetic field in it – at a definite time moment is meant, then the Bean specimen, by demonstrating a constant critical current, always "remembers" the maximal, by the magnitude, value of the applied magnetic field and its sign that occurred in the sample prehistory. In general, depending on the prehistory, the distributions of current density and magnetic field over the specimen can be rather complicated, but a number of parameters which are determined in the CS model are really invariable, if a constant magnetic field is imposed.

In this work, the description of the magnetization reversal process in a thin disk made up of a type-II superconductor in an *ac* magnetic field which was developed in works [1–3] has been extended to include the presence of a *dc* magnetic field directed perpendicularly to the disk plane. The matter was considered in the framework of the same assumptions that were formulated and used in work [3]. An algorithm for writing down the solutions for the radial distribution of azimuthal current density in a thin disk in the case of a multiple change of the external magnetic field variation direction (increase/decrease) has been formulated. Issues concerning what exactly the specimen "forgets" and under which conditions this takes place have been discussed. The consideration demonstrates that, after the temperature and the amplitude of an *ac* field have stabilized, the vortex entry/exit depth, as well as all variable components of specimen characteristics, including the *ac* magnetic susceptibility, acquire their values within a single period of *ac* field oscillations irrespective of the field prehistory and whether a *dc* magnetic field is imposed or not.

2. Results and Their Discussion

Consider a type-II superconductor specimen fabricated in the form of a thin disk of radius R and thickness $d \ll R$. The corresponding London penetration depth $\lambda < d$ (or, if $\lambda > d$, $\Lambda = \lambda^2/d \ll R$). The specimen is cooled down in the ZFC regime. A magnetic field which is parallel to the z-axis is applied perpendicularly to the specimen plane. The field changes quasistatically. We assume that the critical current density J_c does not depend on the magnetic field strength. If the external field h applied to the specimen is low (lower than the corresponding first critical field), the specimen behaves like a specimen made up of a superconductor of the first kind: the magnetic field does not penetrate into the specimen depth (but a near-surface region of the characteristic thickness λ). The external field is completely compensated in the specimen bulk by the field of the azimuthal Meissner current, the distribution of which over the disk radius is [1]

$$J(\rho) = -\frac{4h}{\pi d}\frac{\rho}{\sqrt{R^2-\rho^2}}, \tag{1}$$

where ρ is the distance from the disk center. Hereafter, a current creating a magnetic field which is directed along the z-axis at the specimen center is considered as positive.

When the external field exceeds the corresponding first critical field, H_{c1s}, vortices start to enter the specimen. The value of the "critical field for a specimen" corresponds to an "internal" field in it. The latter is equal to the external field minus the demagnetization one, and, in the case of a thin disk, is much lower than the first critical field for the disk material, H_{c1}. In particular, in the case $\lambda < d \ll R$, we have $H_{c1s} \approx (d/R)^{1/2} H_{c1}$. Pinning centers, if they exist in the specimen, pin the vortices. To describe the vortex entry into the specimen, the critical state model [11] is widely applied. According to it, when the applied field increases, vortices enter the specimen and reduce the local current density to the level of critical current density. The vortex entry depth depends on the critical current density J_c which is determined by the conditions of vortex pinning. Hence, at the stage where the field h monotonously grows from zero, two regions can be distinguished in the specimen. These are an external ring – in which there are vortices, and the current density is equal to $-J_c$ – and an internal circle of radius $a(h)$ – in which there are no vortices, so that the field is equal to zero. As was shown in work [1], the distribution of the current density in this case looks like

$$J(\rho,h)=\begin{cases} -(\frac{2J_c}{\pi})\tan^{-1}\left[\frac{\rho}{R}\sqrt{\frac{R^2-a(h)^2}{a(h)^2-\rho^2}}\right], & \rho\le a(h),\\ -J_c, \quad a(h)\le\rho\le R, & \end{cases} \tag{2}$$

where

$$a(x)=\frac{R}{\cosh(x/H_d)}, H_d=\frac{J_c d}{2}. \tag{2a}$$

The specimen magnetization can be determined using the current density distribution by the formula

$$M=\frac{1}{V}\pi d\int_0^R \rho^2 J(\rho)\,d\rho, \tag{3a}$$

where V is the specimen volume.

The current with distribution (2) creates the magnetization [1]

$$M(h)=-\chi_0 h S(h/H_d), \tag{3b}$$

where

$$S(x)=\frac{1}{2x}\left[\cos^{-1}\left(\frac{1}{\cosh x}\right)+\frac{\sinh x}{\cosh^2 x}\right], \quad \chi_0=\frac{8R}{3\pi d}. \tag{3c}$$

Consider now the case where the field, having reached the value H_0 at the stage of monotonous growth, decreases to the current value h. In the course of such a reduction of the field in the specimen, vortices change their distribution. Formally, this process can be described as an entry of vortices into the specimen, the sign of which is opposite to the sign of those vortices entered at the stage of field growth. In the framework of the critical state model, the entry of those vortices brings about a change of the current density to the value $+J_c$ in an external ring, the width of which is equal to the vortex entry depth. Taking into account that the distribution of the current density and, therefore, the field in the internal circle remain invariable at that, the authors of work [2] showed that the current density distribution at this stage can be represented as a superposition of two currents, the both looking like expression (2). One of them arises owing to the switching-on of the field H_0, and the other is induced by a subsequent variation of the field in the opposite direction by the value $\Delta h_1 = H_0 - h$:

$$J_1(\rho,h)=J(\rho,H_0)-2J\left(\rho,\frac{\Delta h_1}{2}\right). \tag{4}$$

In this case, the quantity $a\left(\frac{\Delta h_1}{2}\right)$ defines the radius of a circle, in which the field remains invariable (vortices do not enter this circle at the stage of field reduction). This circle, in turn, consists of an internal circle of radius $a(H_0)$, in which the field is absent, and a ring with internal and external radii $a(H_0)$ and $a\left(\frac{\Delta h_1}{2}\right)$, respectively, where the field distribution was attained at the previous stage. The coefficient in the second summand reflects the fact that the current density at the specimen edge changes by $2J_c$, when the field changes its direction (the field "reversal"). The formula given remains valid as long as $h\ge -H_0$. At $h=-H_0$, the current distribution looks the same as it was at $h=H_0$, but with the opposite sign. If the field diminishes further, vortices penetrate more deeply into the specimen than they did at the first stage. In so doing, the specimen "forgets" about the first stage, and the current distribution is described by formula (2) with the corresponding substitution of J_c by $-J_c$, as if the field at the second stage changed from the ZFC state rather than $+H_0$.

In the case where the field starts to increase again after having reached some value $H_1 > -H_0$, the corresponding distribution of the current density can be written down analogously as

$$J_2(\rho,h)=J_1(\rho,H_1)+2J\left(\rho,\frac{\Delta h_2}{2}\right)=$$

$$=J(\rho,H_0)-2J\left(\rho,\frac{H_0-H_1}{2}\right)+2J\left(\rho,\frac{\Delta h_2}{2}\right), \tag{5}$$

where $\Delta h_2 = h - H_1$ is the difference between the current field value and the field value at the last reversal of a field variation direction. Similarly to the previous case, the field distribution that arose at the previous stages remains invariable in the circle of radius $a\left(\frac{\Delta h_2}{2}\right)$, whereas the current density in the external ring of width $R-a\left(\frac{\Delta h_2}{2}\right)$ is critical. Formula (5) also remains correct until the depth of vortex entry at this stage exceeds the entry depth at the previous stage, i.e. as long as $h\le H_0$. When the value $h=H_0$ is attained, the last two summands in Eq. (5) are mutually compensated, so that the specimen "forgets" about the last two stages of field variation.

Hence, one can create an algorithm for constructing a formula which would describe the current density distribution in the general case and at an arbitrary sequence of quasistatic variations of the field h after the ZFC state. Let the field, alternately increasing and decreasing in the course of such variations, attain the values H_0, H_1, H_2,…, H_N at the "reversal" points. Introducing the notation $J_{i-1}(\rho)$ for the current distribution over the specimen at the time moment when the field achieved the "reversal" point $h = H_i$, one can write down the following recurrent formula for the current density distribution, provided that the field varies monotonously after this point:

$$J_i(\rho, h) = J_{i-1}(\rho) \pm 2J\left(\rho, \frac{\Delta_i h}{2}\right), \tag{6}$$

where $\Delta_i h = |h - H_i|$. In this case, the absolute value of current density in the external ring of the width $R - a\left(\frac{\Delta_i h}{2}\right)$ is equal to the critical current density, and the field in the circle of radius $a\left(\frac{\Delta_i h}{2}\right)$ remains invariable and equal to that created at the previous stages. At the center, there is a circle, where the field equals zero. The radius of this circle, $a(H_{\max})$, is determined by the maximal, by the absolute value, field $H_{\max}$ applied to the specimen. The sign before the second term in Eq. (6) is determined by the field variation direction after the point $h = H_i$: it is plus, if the field increases, and minus, if it decreases. This formula remains correct until the vortex entry depth attained at this stage of field variation exceeds the corresponding value attained at the previous stage. If there are no stages with monotonous field variation, at which the vortex entry depth exceeds that reached at the previous stage, one may say that the specimen "remembers" the whole history of imposed external magnetic fields that took place after the ZFC state, and formula (6) can be presented as the sum

$$J_N(\rho) = J(\rho, H_0) + 2\sum_{i=1}^{N} (-1)^i J\left(\rho, \frac{\Delta_i H}{2}\right), \tag{7}$$

where $\Delta_i H = |H_i - H_{i-1}|$.

If vortices penetrate more deeply into the specimen at the j-th stage than at the previous one, two summands (j-th and $(j-1)$-th) disappear from this sum (i.e. the specimen "forgets" about the corresponding stages), and H_{j-2} in the $(j-2)$-th term is to be substituted by H_j. At the same time, if the vortex penetration depth becomes larger at some stage than it was at every previous stage, all terms that describe stages before this one disappear from the sum. This means that the field maximal by its absolute value can be taken as H_0, and all previous stages of field variation can be excluded from consideration.

Let a magnetic field $h = H_{DC} + h_{ac}$, where $H_{DC} > 0$ is a constant field and h_{ac} is a current value of an ac field that oscillates between its peak values $\pm h_0$, be applied to the specimen perpendicularly to its plane. When the total field achieves the value $H_{DC} + h_0$, a certain distribution of current density, which we denote as $J_{\max}(\rho)$, is established in the specimen. Provided that no field higher than $H_{DC} + h_0$ was applied to the specimen before, the distribution $J_{\max}(\rho)$ is determined by formulas (2) and (2a), in which the vortex-free circle radius is equal to $a(H_{DC} + h_0)$. Otherwise, the current density distribution $J_{\max}(\rho)$ depends on the field variation history before the field reaches the value $H_{DC} + h_0$.

If the total field diminishes further from $H_{DC} + h_0$ to $H_{DC} - h_0$, the current density distribution is described by formula (6):

$$J(\rho, h) = J_{\max}(\rho) - 2J\left(\rho, \frac{h_0 - h_{ac}}{2}\right). \tag{8a}$$

At the next stage of field growth from $H_{DC} - h_0$ to $H_{\mathrm{DC}} + h_0$, the current density distribution looks like

$$J(\rho, h) = J_{\max}(\rho) - 2J\left(\rho, h_0) + 2J(\rho, \frac{h_0 + h_{ac}}{2}\right). \tag{8b}$$

When the field achieves the value $H_{DC} + h_0$, the last two summands in Eq. (8b) become mutually compensated, the current density distribution coincides with $J_{\max}(\rho)$, and formula (8a) becomes applicable again at the next stage where the field decreases. The maximal depth, to which vortices of different signs will alternately enter at subsequent h_{ac}-oscillations – i.e. the width of the external ring, within limits of which a redistribution of the field in the specimen will take place – will be determined by only the varying part of the external field. Namely, it will be equal to $R - a(h_0)$, whereas the magnetic field within the limits of the circle $\rho < a(h_0)$ will remain invariable. At the same time, the current density distribution will change in the circle $\rho < a(h_0)$ too, tracing a current position of the vortex penetration depth a (see formula (2)).

Substituting Eqs. (8a) and (8b) into Eq. (3a) and denoting the specimen magnetization at $H_{DC} + h_0$ and $H_{DC} - h_0$ as $M_{\max}$ and $M_{\min}$, respectively, we obtain the following formula for magnetization at the stage where the ac field decreases:

$$M_-(h) = \frac{\pi d}{V} \int_0^R \rho^2 J_{\max}(\rho)\, d\rho -$$

$$-\frac{\pi d}{V} \int_0^R \rho^2 2J\left(\rho, \frac{\Delta_- h}{2}\right) d\rho = M_{\max} - 2M\left(\frac{\Delta_- h}{2}\right), \tag{9a}$$

where $\Delta_- h = h_0 - h_{ac}$. Accordingly, at the stage where the ac field increases, we have

$$M_+(h) = \frac{\pi d}{V} \int\limits_0^R \rho^2 (J_{\max}(\rho) - 2J(\rho, h_0)) d\rho +$$

$$+\frac{\pi d}{V} \int\limits_0^R \rho^2 2J\left(\rho, \frac{\Delta_+ h}{2}\right) d\rho = M_{\min} + 2M\left(\frac{\Delta_+ h}{2}\right), \quad (9b)$$

where $\Delta_+ h = h_0 + h_{ac}$. Both quantities $\Delta_- h$ and $\Delta_+ h$ stand for a difference between the current field value at the corresponding stage and its value at the last field "reversal", and both do not depend on H_{DC}. The formulas obtained allow two basic conclusions to be drawn. First, the identical dependences of a magnetization change on the field variation at the stages of field decrease and increase leads to the symmetry of a hysteresis loop with respect to the point $\left(H_{DC}, \frac{M_{\min}+M_{\max}}{2}\right)$. Second, the dependence of the variable part of the magnetization on only the ac field means that the hysteresis loop shape does not depend on the dc magnetic field.

In work [3], an interrelation between the critical current density and the dependence of complex magnetic susceptibility harmonics of a thin-disk-shaped specimen on the ac magnetic field amplitude h_0 $h(t) = h_0 \cos(\omega t)$ directed perpendicularly to the disk plane was considered. The harmonics of the real and imaginary parts of the ac magnetic susceptibility are defined by the formulas

$$\chi'_n = \frac{\omega}{\pi h_0} \int\limits_0^T M(t) \cos(n\omega t) dt, \quad (10a)$$

$$\chi''_n = \frac{\omega}{\pi h_0} \int\limits_0^T M(t) \sin(n\omega t) dt. \quad (10b)$$

Substituting expressions (9a) and (9b) into them, we obtain that, owing to the averaging over the period of the ac field, those components of the magnetic moment of a specimen that depend on the dc field magnitude do not make any contribution to harmonic amplitudes, and, therefore, the latter depend only on the ac field strength.

When applying the CS model to the description of processes in specimens, the issue concerning the influence of a prehistory of variations of the dc and ac components of the magnetic field, without returning to the ZFC state, on the ultimate results is of importance. Every change of the applied field is accompanied by a variation of the azimuthal current density distribution in a specimen and, as a consequence, by a variation of the magnetic moment of the specimen. As a result, after a number of reversals of the applied field variation direction, a quite complicated distribution of current density over the specimen, which is described by formula (7), can emerge.

However, the actual state of the specimen can depend not only on the prehistory of magnetic field changes, but also on the temperature by means of the temperature influence on the critical current density. In the case where the dc field is constant, and the critical current density increases – e.g., as a result of temperature reduction – the external field at the center of a specimen remains completely compensated by the existing current distribution, and the current density in the specimen does not exceed the critical value anywhere. Hence, neither new vortices enter the specimen, nor a redistribution of vortices takes place in it. Therefore, the growth of the critical current density is not accompanied by a change of the current and field distributions in the specimen that existed at that moment. However, the conditions for the vortex motion do change, so that formula (7) loses its validity for the description of subsequent variations of the magnetic field.

In the case where the temperature grows, provided that the field is constant, which results in a reduction of the critical current density, the motion of those vortices which have entered the specimen at the previous stage of field variation, becomes restored, and the entry of new ones continues. Vortices enter the specimen, move toward its center, and expand the external ring formed at the previous stage until the current density in this ring falls down to the actual critical value. In this case, the formulas presented above lose their applicability again. Though the influence of the prehistory of critical current density variations on the specimen state can also be considered in the framework of the CS-model formalism, this problem, however, is not the subject of this work. Concerning the issue of the specimen "memory" at a constant critical current density, one may assert that, at any variations of the applied field, there will remain a vortex-free circle at the center of the specimen, the radius of which will be determined by the maximal value of a field applied to the specimen.

The distribution of the current density in the specimen can be rather complicated. Nevertheless, as was shown above, when both the ac and dc fields are simultaneously imposed perpendicularly to the specimen plane, the current density distribution, as well as the magnetic moment, can be divided into two components. One of them does not depend on the current value of the *ac* field (though it depends both on the magnitude and the prehistory of the *dc* field), and the other depends only on the amplitude and the actual value of the *ac* field. Therefore, after the maximal, by magnitude, field – i.e. the sum of the constant and alternating components – has been reached, the current density distribution changes cyclically with a period equal to that of the *ac* component of the applied field. This means that the prehistory of establishing the *dc* field or the temperature can affect the results of determination of the variable part of the magnetic moment within one period of the *ac* magnetic field only.

In view of the fact that the relations of the CS model are widely used for the interpretation of experimental results, it should be noted that, in this work, the subject of consideration was an answer to the theoretical question "What will happen, if a constant magnetic field is imposed on the specimen, provided that the consideration is carried out in the framework of the Bean critical state model and Clem and Sanchez's additional assumptions are made?" An answer to another question, "Which accuracy does the CS model provide for the description of processes in real specimens?", does not basically depend on adding a *dc* magnetic field. This question requires a separate consideration in every experimental situation, so that it has not been analyzed in this work.

3. Conclusions

Hence, the Bean specimen always "remembers" the highest value of applied magnetic field in its prehistory. Although after multiple changes of the applied field or temperature have been made, the specimen state can be described by rather complicated distributions of current density and magnetic field in it, the magnetic moment of the specimen can be divided into two components not later than in the applied *ac* field period. One of them depends on the *dc* field and can partly "remember" the prehistory. It does not depend on the actual value of the *ac* field. The other depends only on the *ac* field (its amplitude and the actual value).

In the framework of the critical state model, the relations obtained by Clem and Sanchez for the *ac* magnetic susceptibility of a thin disk do not change, if a constant component of the magnetic field directed perpendicularly to the disk plane is added. Consequently, they can be used in experimental researches aimed at studying the dependence of the critical current density on the magnetic field in cases where this dependence can be neglected (the interval of total field variation within the period of *ac* field oscillations is narrow enough). The reliability of the results obtained turns out to be the same as that allowed by the CS model for the description of processes in real specimens without imposing a constant field.

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ПЕРЕМАГНІЧУВАННЯ ТОНКОГО
ДИСКА НАДПРОВІДНИКА 2-ГО РОДУ
ЗА НАЯВНОСТІ ПОСТІЙНОГО МАГНІТНОГО ПОЛЯ

Д.Г. Ковальчук, М.П. Чорноморець

Р е з ю м е

В рамках моделі критичного стану розглянуто питання застосовності отриманих Клемом і Санчезом співвідношень для змінної (*ac*) магнітної сприйнятливості тонких плівок надпровідника 2-го роду у випадку наявності постійного магнітного поля, перпендикулярного площині плівки. Обговорено питання "пам'яті" зразка і вплив передісторії змін магнітного поля на поточний стан зразка. Показано, що *ac* компонента магнітного моменту, а, отже, і амплітуди гармонік *ac* магнітної сприйнятливості, встановлюються протягом одного періоду *ac* магнітного поля незалежно від передісторії.