THE ABNORMAL HYSTERETIC PHENOMENA IN MAGNETIC FIELD

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In this paper we try to summarize experimental data and theoretical models on abnormal hysterestic phenomena of high-T_c superconductors (HTSC) critical current. The main emphasis is made on high magnetic field $H >> H_{c1}$ since there is the most concluding theory based on the field dependence of critical current of a single Josephson contact.

1. Introduction

Several authors, for instance [1–17], have shown experimentally that in granular HTSC like sintered YBCO and BSCCO samples the critical current J_c is hysteretic in an applied magnetic field. For decreasing fields, the critical current was larger than for increasing one. In many cases such abnormal hysteresis in physical characteristics of metaloxides can be associated with the unambiguous dependence of their critical current on the magnetic field.

The authors of [1–11,15–17] believe that the physical cause of hysteretic behaviour of critical current J_c in ceramics is susceptibility of weak link critical current to local intergranular fields. The essence of the models proposed is that the magnetic flux portion trapped by granules can change their direction at the reversal of the external magnetic field resulting in weakening of the intergranular local field. The compensation models of this kind can, at least qualitatively, explain the hysteresis of J_c in low fields $H < 100$ Oe when the magnetization of grains M_g associated with the flux trap is comparable with the external field magnitude. Hysteretic phenomena, however, are also observed in very high fields $H \geq 3$ kOe [5–6,9–11,13–15] when inequality $\mu_0 H >> M_g$ is fulfilled. Therefore the magnetic flux trapped by the granules cannot weaken the intergranular field considerably.

The systematic investigation performed in works [12–14, 18–26] shows that the hysteretic phenomena in the metal ceramics critical current and, perhaps, in other characteristics of metaloxides [1–17] can be quite adequately explained by the hysteresis of critical current I_c of intergranular contacts even if intergrain local field is not enhanced.

The point is that in the most general case the response of critical current I_c of the Josephson junctions to magnetic field H is determined not only by the magnitude of field H within the superconducting electrodes, as is usually believed, but rather by the magnitude of the surface current j_{sf} [18–21] induced in the granules. This current, in accordance with the Maxwell equation $j_{sf} = dH/dx$, is set by the field derivative H along normal (x) to the field and sample surface. If within the superconducting granules of Josephson junction there are no Abrikosov vortices j_{sf} is equal to the Meissner screening current j_{sm} decreasing exponentially inside superconducting electrodes $j_{sm} = j^0_{sm} \exp(-x/\lambda_g)$, where λ_g is the London field penetration depth. As a result, the critical current I_c of small-sized Josephson contacts ($W < \lambda_j$) depends directly on the external magnetic field

$$I_c\{j_{sf}(H)\} \equiv I_c(-dH/dx) = I_c(H/\lambda_g). \quad (1)$$

Here W is the size of a weak place of the junction in the direction perpendicular to field H, λ_j is the Josephson penetration depth of the magnetic field into the junction region. We assumed here that surface barrier to Abrikosov vortex motion is absent. Another limit is considered in paper [27].

Once the Abrikosov vortices penetrate to the junction there is an additional component of the surface current j_c^g due to the density gradient of these vortices. As a result, when there are vortices within the granules, the surface current j_{sf} consists of the reversible "Meissner" component j_{sm} whose sign is set by the external field direction and the irreversible component j_c^g due to the fluxoid pinning (j_c^g is the granule critical current). In increasing field $H_\uparrow$ the vortex density in the volume of granules is less than in the center and j_c^g added with j_{sm}, $j_{sm}(H^\uparrow) \cong j_{sm} + j_c^g$. In decreasing field $dH_\downarrow$ the distribution of the vortex density is reverse, so j_c^g changes its sign whereas the sign of j_{sm} associated with the intergranular field direction is preserved. The total density of the surface current decreases, i.e. $j_{sf}(H^\downarrow) = j_{sm} - j_c^g$.

The difference in surface currents of $j_{sf}^\uparrow$ and $j_{sf}^\downarrow$ of granules results in the hysteresis of critical current J_c in ceramics since $J_c \sim J_c / a_0^2$ and for some Josephson junctions the critical current in an increasing field is less than in a decreasing one [13,14,21],

$$J_c\left[2\lambda_g^2 j_{sf}^\uparrow + tH\right] < J_c\left[2\lambda_g^2 j_{sf}^\downarrow + tH\right]. \quad (2)$$

Here the item tH is due to the magnetic field penetration to the intergranular spacing t, i.e. t is the Josephson contacts length; usually $t << \lambda_g$; a_0 is the characteristic size of the percolation network cell in a granular superconductor (in the particular case — the grain size).

In accordance with (2) in an intermediate field region

$$H_{c1} < H << \left[2\lambda_g^2/t\right] \, |j_{sf}|$$

the strong hysteresis should be observed if components j_{sm} and j_c^g of the granule surface current are of the same order of magnitude. For YBCO $H_{c1}^g \sim 50 \div 100$ Oe, $\lambda \approx \lambda_{ab} \approx 0.2\,\mu$m ($T = 77$ K) thus the equilibrium part of the surface current is $j_{sm} \sim H_{c1}^g/\lambda \sim 10^6$ A/cm^2 and the densities of the granule critical currents j_c^g are just within this range.

2. Physical nature of the critical current hysteresis of granular materials in high magnetic fields

Let us perform the qualitative analysis of anomalous hysteresis of the granular superconductor critical current. The full calculation of the $J_c - H$ dependence for the particular case of a junction with the flat granules is given in [20,23–25]. The numeration (1–10) on the design curve $J_c(H)$ (Fig. 1) denote the positions for which the qualitative analysis of the current and magnetic field distribution in the granular structure is made. The intergranular critical current density is assumed to be much less than intragranular one. Therefore the arrows in Fig. 1 denote only the direction of intragranular currents. One can also assume that the width W of weak links is small as compared with the Josephson penetration depth of magnetic field λ_J, $W<\lambda_J$. This condition simplifies the analysis in intermediate magnetic fields $H \leq \Phi_0/(\lambda_J \lambda_g) = H^J_{c1}$. In high fields, however, $H >> H_{c1} > H^J_{c1}$, the magnetic flux in intergrain space becomes homogeneous. So the properties of wide ($W >> \lambda_j$) and narrow ($W \leq \lambda_j$) Josephson junctions in the magnetic field are almost the same [28].

Here and below we understand the magnetic field as local field H penetrated into the intergranular space. The magnitude of this field is set by the current distribution in the intergrain cluster and can be found, for example, in the critical state model for the granular specimen [29–31]. Therefore the local intergrain field H is assumed to be set. Nonuniformity of the current distribution in the specimen can be also the cause of the hysteresis in the ceramics critical current. Thus due to the trap of vortices in the granules the ceramics critical current can become smaller. These hysteretic effects are noticeable only at small fields $H << J_c(H)\, d/2 = H^j_p$ or in essentially non-uniform specimens [29–31]. We, however, are interested here in the field range $H >> H^j_p$, where the condition $H >> M_g$ is fulfilled. Here the grains magnetization $M_g \approx (D/6)\, j^g_c$, D is the grains diameter, j^g_c is the intragrain critical current. For $j^g_c \sim 10^6$ A/cm^2 and $D \sim 4\,\mu$m $M_g \sim 100$ Oe.

Further on we shall also neglect the effects due to the demagnetizing factor of the grains since they do not affect in any way the qualitative results. We also neglect the vortex lattice structure since the hysteretic effects are mostly caused by the dependence of the vortex density gradient on the specimen magnetic prehistory and by the presence of reversible surface current. The structural distortions of the vortex lattice can, however, result in a more rapid decrease in the critical current of weak links as a function of magnetic field [18,32].

Let the specimen be cooled in a zero field (the ZFC case). At the initial stage Fig. 1, (1), the external field $H < H^g_{c1}$ induces the Meissner current j_{sm} in the granules which flows in their surface layer $\sim\lambda_g << D$ thick. In Fig. 1 this small region of the Meissner current penetration is denoted by the contour on the granule surface. Once the magnetic field H exceeds H^g_{c1} the Abrikosov vortices penetrate into the surface layer of the granules, their density gradient gives rise to the additional screening current j^g_c whose direction is shown by solid arrows Fig. 1, (2). At $H > H^g_{c1}$ the Meissner current magnitude is restricted and determined on the granule surface by the equilibrium (Abrikosov) magnetization $M_{eq} \approx H_{c1}$, $j_{sm} \cong M_{eq}/\lambda_g$. The field H in the intergrain space and induction B_0 on the grain surface being connected by relationship $B_0/\mu_0 = H - M_{eq}$ [33,34]. The restriction of value j_{sm} results in a sharp weakening of the response of the Josephson junction critical current to the magnetic field $H \geq H^g_{c1} + \lambda_g j^g_c = H^*_{c1}$. The inflection point on the J-H dependence at $H \cong H^*_{c1}$ corresponds to the transition of the granules in a mixed state.

Up to the moment when the external field starts to drop the irreducible part of the granule, surface current j^g_c has the same direction as the Meissner equilibrium screening current whose magnitude is set by the induction jump at the specimen boundary. This jump is shown schematically in the figures illustrating the field distribution Fig. 1, (3).

At point Fig. 1, (5) the external field starts to decrease. The vortex density on the granule boundaries decreases but due to magnetic flux pinning effects within the granules the density of vortices is higher. Therefore in the surface layer the gradient of the Abrikosov vortex density and, consequently, the intergranular current j^g_c changes its direction. The direction of the Meissner component of the surface current j_{sm} is preserved since it is associated with the sign of the external field. The Fig. 1, (7) shows the point of "full compensation" where the equilibrium (Meissner) current component j_{sm} and surface critical current of the granules j^g_c compensate each other $j_{sm} - j^g_c \approx 0$. So the maximum of Josephson critical current in decreasing field $H\downarrow$ can be observed in the vicinity of field H^*, where $j_{sf}(H^*) \approx 0$, $H^* \approx H_{c1}/\lambda$.

If the field in intergranular layer turns to zero the gradient of the magnetic flux trapped in the granules makes surface current $j_{sf} \cong j^g_c$ suppressing the critical current of weak links (Fig. 1, (8)). This suppression of J_c is equivalent to the existence of an effective field $H_{\text{eff}} = \lambda j^g_c$. An additional suppression of the transport critical current may be also due to the effects of the field of currents flowing through the intergrain contours. It should be noted that $H^* \approx H_{\text{eff}}$, i.e. the effective field H_{eff} value can be obtained from the experimental curves as the field $H^{\downarrow} = H^*$ which corresponds to the critical current maximum. The corresponding reduced critical current value $J_c(0\downarrow)$ of specimen is

$$J_c(H\downarrow \to 0) \approx J_c(H^{\uparrow} = H^*) . \tag{3}$$

The equality (3) is in agreement with some experiment quite well |1–2,7–10|.

In the actual ceramic specimen the magnetic field direction in the intergranular space in the general case does not lie in the intergrain junction plane. We believe that the flux in the granules is rigidly fixed. Therefore only the field component lying in the junction plane is actually operating. Due to the spatial averaging the singularities in the theoretical curve get smeared. Therefore the observed fulfillment of the equality (3) is surprising.

The qualitative considerations given above show that the positions of the main typical points in the $J_c(H)$ curve only slightly shift due to this averaging. This is first of all point corresponding to the initial stage of the Abrikosov vortex penetration at $H^{\uparrow} \approx H^*_{c1}$, point at which the surface currents are almost totally compensated $H\downarrow = H^*$ and point corresponding to the suppression of the intergranular critical current with the magnetic flux trapped by the granules (3).

3. Conclusions

The obtained results allow one to understand the physical sense of the main singularities on the J_c vs H curves for metalceramics. At the initial stage at $H > H_{c1}^{g}$ the critical current of intergrain links drops considerably as a function of

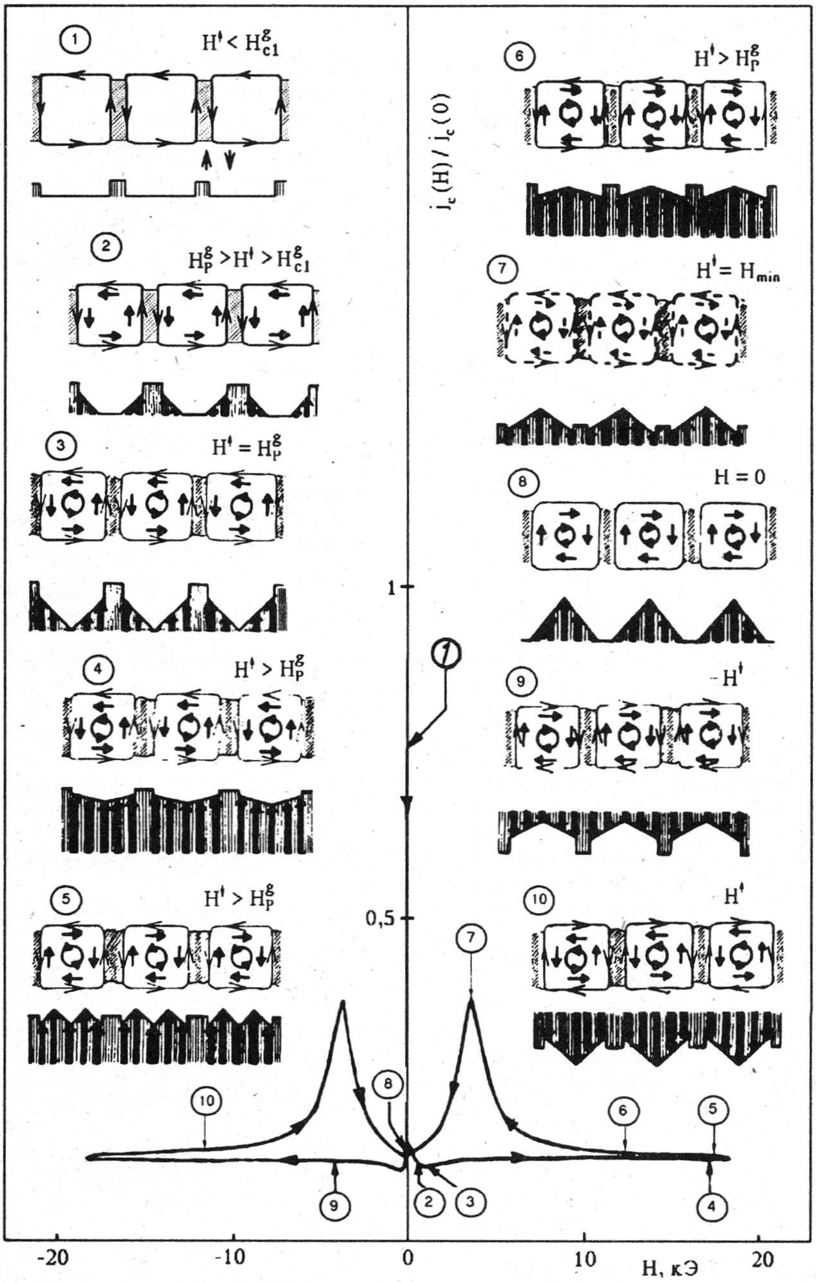

Fig. 1. The calculated hysteresis loop $J_c(H)$ and configurations of magnetic fields and superconducting currents in Josephson connected granules at high fields (see the text)

constant external field. At $H > H_{c1}^{g}$, however, the Abrikosov vortices penetrate into granules and, consequently, the intergranular current starts to depend not on the field value itself but rather on the value of the surface current induced by this external field in granules, i.e. on derivative dH/dx where coordinate x is directed inside the granule. As a result, on the curve $J_c(H)$ there is an inflection point at $H \approx H_{c1}^{*} = H_{c1} + \lambda_g j_c^g$.

When the external field changes its direction the irreducible part of the granular surface current due to pinning also changes its direction. Therefore the total surface current becomes lower. This giving rise to the growth of the intergrain junction critical current. The J_c maximum is observed at the field point when almost full compensation of the granular surface current is achieved, i.e. when $j_{sf} \approx 0$. When the external field is zero the density gradient of the remained vortices in the granules determines the corresponding magnitude of the surface current which depressed the critical current in ceramics.

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