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Analysis of Superconductor Magnetization Hysteresis

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The critical state model and the extended critical state model are described to analyse a magnetization hysteresis and to find superconductor parameters. We discuss how geometric sizes and form influence on magnetization hysteresis, critical current and trapped flux.

Keywords: pinning, Abrikosov vortices, critical state, critical current density, trapped flux.
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An essential criterion of superconductivity in studied samples is sharp drop of the resistance at some temperature. Other essential criterion is a great diamagnetic response during the magnetization measurements. Temperature and magnetic field dependencies of the magnetization give the detailed characterization of the superconducting phase in single-crystal and polycrystalline samples.

The critical state model [1] and its many modifications describe entering and trapping of magnetic flux in a II-type superconductor. The extended critical state model [2–4] accounts contributions to the magnetization loop from the surface and the internal volume of a superconducting sample. The extended model allows to parametrize the magnetization hysteresis with asymmetry relative to the $M = 0$ axis.

1. Determination of superconducting parameters from magnetic measurements

The critical current density j_c is most important parameter for superconductor applications. The diamagnetic response is determined by j_c. The critical state model [1] results in the Bean formula $j_c = 3\Delta M/2R$, such that one can estimate j_c from the magnetic measurement. In the Bean formula ΔM is the hysteresis width, R is the radius of the current circulation.

Main stages of magnetization hysteresis analysis are given below.

1. The content of a superconducting phase should be estimated firstly. The virgin magnetization changes as $M(H) = -xH$ for $H < H_{c1}$, here x is the content of a superconducting phase. The demagnetization factor can distort the value of x. Additional diamagnetic [5] / paramagnetic [6, 7] phases in a sample tilt the magnetization hysteresis clockwise / anticlockwise. Coexistence of superconducting and ferromagnetic phases in a sample gives a composite hysteresis [8]. For hysteresis of the superconducting phase the dependence of M on H approaches to 0 as H increases to the upper critical field H_{c2}.

2. Some special fields are remarkable on a hysteresis and can be estimated directly (Fig. 1). The lower critical field H_{c1} is the point in which the virgin $M(H)$ dependence begins to deflect from the linear line. The virgin $M(H)$ dependence becomes to coincide with the envelop magnetization loop at $H = H_p$, the full penetration field. The $M(H)$ dependence becomes reversible at H higher than the irreversibility field H_{irr}. The superconductivity and the corresponding

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diamagnetic response disappear at H higher than the upper critical field H_{c2}. The trapped magnetic flux B_{tr} in a sample equals to $\mu_0 \Delta M$ at $H = 0$.

3. The depth of the magnetic field penetration λ_0 can be estimated from the reversible part of magnetization hysteresis. The London model [9] results in formula for the equilibrium magnetization $M = -\phi_0/(32\pi^2\lambda_0^2)ln(\eta H_{c2}/H)$, where ϕ_0 is the magnetic flux quantum, η is a constant about 1.

4. The hysteresis width is defined by the product of j_c and R such that the current circulation scale should be found for estimations of j_c from magnetic measurements. There is a problem here because the size of current circulation R can differ from the sample radius. It may be the effective grain radius for polycrystalline samples or a size of grain clusters. The hysteresis asymmetry relative to the $M = 0$ axis allows to estimate R because this asymmetry depends on R but it is independent of j_c. The asymmetry is defined by the ratio of l_s/R, where l_s is the depth of the surface layer with equilibrium magnetization [2, 3]. Abrikosov vortices are not pinned in this surface layer. The value of l_s is not larger than λ_0. Noticeable asymmetry of hysteresis is observed for $l_s/R > 0.1$ such that one can estimate $R < 10\lambda$ for asymmetric magnetization hysteresis. For analyzed polycrystalline superconductors the magnetization loops are good fitted by the extended critical state model with R equal to the average grain radius obtained from SEM.

5. The $j_c(H)$ dependencies are easy plotted from the magnetization loops by using the Bean formula. These j_c values obtained are the critical current density averaged on the cross-section perpendicular to the external magnetic field H. Then the field dependence of the pinning force $F_p(H) = \mu_0 H j_c(H)$ is plotted that allows to find the maximal pinning field and H_{irr} also. If the second peak (fishtail, peak effect) is noticeable on a magnetization hysteresis and on field dependencies of j_c and F_p than the peak position and its temperature evolution contain information about the vortex lattice transition or the phase separation in superconductor [5].

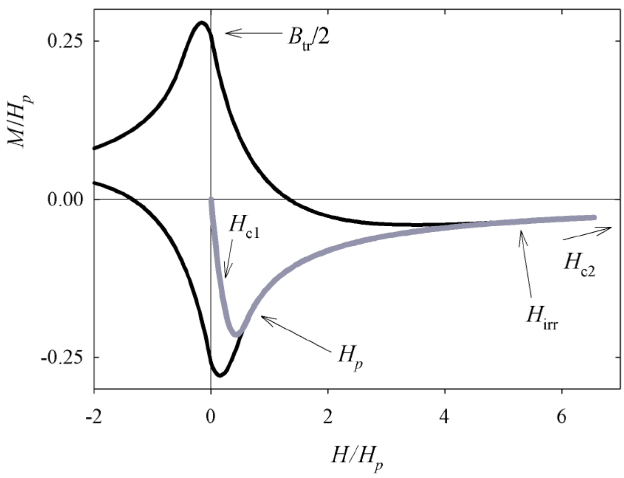

Fig. 1. Characteristic fields on magnetization hysteresis of superconductor. The H_{c2} field is more larger than a maximal external field

As the extended critical state model describes, the averaged critical current density j_c depends on the size and the form of the sample. Due to the surface layer the averaged critical current $j_c = j_{cb}(1 - l_s(H)/R)^n$, here j_{cb} is the critical current density of a macroscopic sample with sizes more larger than λ_0, n is the parameter defined by the sample form, $n = 3$ for the long cylindric sample and $n = 2$ for the long plate parallel to H (Fig. 1).

Review article [3] has some additional references on application of the extended critical state model to analysis of magnetization loops of different superconductors.

Conclusion

Magnetization hysteresis analysis gives some parameters of superconductors: the lower H_{c1} and upper H_{c2} critical fields, the full penetration field H_p, the irreversibility field H_{irr}, the trapped flux B_{tr}, the equilibrium layer depth l_s, the critical current density j_c. When sizes of a sample/grains are comparable with the magnetic field penetration depth λ_0, the magnetization hysteresis is asymmetric and the extended critical state model should be applied to describe this. The averaged critical current density decreases with the sample/grain sizes due to equilibrium magnetization of the surface layer. Also the sample/grain sizes and their form influence on the magnetization hysteresis form, particularly on the pinning force maximum field.

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Анализ петель намагниченности сверхпроводников

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Описано использование модели критического состояния и расширенной модели критического состояния для определения параметров сверхпроводников из измеренных петель намагниченности. Обсуждается влияние геометрических размеров и формы образцов на вид петель намагниченности, критический ток и замороженное магнитное поле.

Ключевые слова: пиннинг, вихри Абрикосова, критическое состояние, плотность критического тока, захваченное поле.