Synopsis

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Title: Complex susceptibility and pinning potential in low anisotropic superconductors

Depending on the pinning landscape in superconducting systems the enhancement in the critical current density is possible. Even though in experimental studies it is extremely difficult to have an exact idea about the pinning landscape, in numerical studies it is not impossible. Following different theories attempts have been made to obtain the way of attaining maximum critical current. However, it is very important to understand how local pinning force density affects critical current density. Internal field profile in presence of any particular pinning landscape governs local current density which is very essential to overall enhancement. Complex susceptibility and pinning potential are known to be strongly related via the local field profile. In the present work we have addressed different aspects of the aforementioned ideas in low anisotropic superconducting systems in which pinning potentials are known to be very strong. Critical state model is known to be very successful in finding the local field profile in a superconducting system [K. H. Muller, Physica C 159 (1989) 717]. We have proposed that the pinning force density depends not only on temperature but also on the position coordinate. We have modified and followed the finite temperature critical state model to calculate the complex susceptibility as a function of temperature. We have considered low anisotropic superconducting systems within the framework of the critical state model. An inhomogeneous granular superconductor is numerically subjected to an ac magnetic field. Individual superconducting grains and intergranular regions have different pinning strengths and a related pinning force density profile is intrinsic inside any such combined systems which has been modelled [S. Roy, Ajay Kumar Ghosh, Physica C 580 (2021) 1353766]. A superconducting sample is modelled as grain-clusters (g) with a fixed number of 215 grains per cluster, separated by nongrained regions (J). Length of one granular region is $215 \times 2R_g$ where R_g is the grain radius. One nongrained region and one grained region together form one composite segment. There are five such composite segments of equal length in each half of the sample. An ac magnetic field with angular frequency ω= 314.15 and amplitude $H_m^a = 200$ is used externally. The critical state equation of the following form is solved for the magnetic field inside the sample

$$\frac{dH_J(x,t)}{dx} = \pm\frac{1}{\mu_0\mu_{eff}(T)}\frac{\alpha_J(x,T)}{|H_J(x,t)|+H_{0J}} \qquad (1)$$

$H_J(x,t)$ is the local field in the nongrained region at any time instant t. $\alpha_J(x,T)$is the pinning force density in nongrained region. We have used a constant value for H_{0J}= 0.1. μ_{eff} is the effective permeability of the sample. A functional form of the pinning force density $\alpha_{J(g)}(x,T)$ is considered with separation of variables of temperature and position in both g and J regions as given below:

$$\alpha_{J(g)}(x,T) = \alpha_{J(g)0}(x)\left(1-\frac{T}{T_c}\right)^2 \qquad (2)$$

We have considered two functional forms for the position-dependent pinning force density, $\alpha_{J(g)0}(x)$ (i) the repetitive Gaussian (RF) function and (ii) Rademacher (RD) function.
We have studied the internal field profile in a network consisting of the superconducting grains and intergranular region using at first only the repetitive Gaussian pinning force density profile [S. Roy, Ajay Kumar Ghosh, Physica C 580 (2021) 1353766]. The internal magnetic field as a function of the

Shoumi Roy
08/04/2022

position inside the superconductor exhibits nonlinear, step-like nature. The complicated nature of the penetration of the field gets strongly affected by the size of the granular region, which is changed gradually with R_g/d = {0.8, 2.0, 2.8, 3.6}x 10^{-4} where R_g is the grain radius and d is half the sample length, and the total pinning force density in the superconductors. At temperature T = 15, penetration depth changes from 0.13 for R_g/d =0.8 x 10^{-4} to 0.62 for R_g/d =3.6 x 10^{-4}. We have numerically calculated real and imaginary parts of complex susceptibility. The variation of the imaginary part with temperature has a peak at a temperature T_p which shifts towards the lower temperature with the increase of the superconducting fraction. T_p ranges from 36.5 for R_g/d =0.8 x 10^{-4} to 23.25 for R_g/d =3.6 x 10^{-4}.

Next, we consider samples with more extreme grain radii R_g/d = {0.4, 4} x10^{-4} [S. Roy et al. "*Dynamics of local magnetic field profile in disordered superconductors*", 2021, submitted]. The grain radii is varied by an order of magnitude to qualitatively probe the sensitivity of the local and global magnetic phenomena to grain radii and hence superconducting fractions. Here both Rademacher function and repetitive Gaussian forms of the pinning force density have been modelled. Same arrangement of 5 composite regions of non-grained regions and grain clusters is also assumed. Staircase like field penetration is observed in the samples with the field remaining constant or nearly constant over the grain cluster. Over a wide range of temperature below the critical temperature T_c=51, we have calculated and analysed local field profile at different time instants in the ac cycle. Comparison between the field profiles in samples with different pinning illustrates the local dependence of magnetic properties of the sample on the pinning profile. At t = 0.006, we can clearly see that though the local field profile is not identical throughout the non-grained region, the values of the magnetic field at the surface and at the beginning of the grain cluster are nearly equal. Comparison between the susceptibility vs temperature graphs of the two differently pinned samples illustrates the global dependence of the magnetic properties of inhomogeneous superconductors on pinning profiles. The peak temperature, T_p increases with the increase the pinning force density in samples irrespective of the functional form. For sample with Rademacher (RD) pinning and R_g/d = 4 x10^{-4}, T_p varies from 14.75 to 48.63 for change in magnitude of pinning constants (α_s) from 2.4 x10^5 to 5.4 x10^7. The difference between the peak temperatures for samples with different radii decreases with increase in pinning magnitude. This difference in T_p for RD pinned samples varies from about 7 for α_s = 2.2 x10^6 to about 1 for α_s =5.4 x10^7. T_p tends to transition temperature T_c for higher values of pinning potentials.

We have also undertaken 2D extension of the model as a step towards the understanding of more complicated and more realistic sample geometry, defect geometry and hence pinning due to such defects. 2D extension of the model is undertaken under the assumption of independent, decoupled pinning properties along the two directions of the sample perpendicular to the applied field. We start with identical pinning properties along both x and y directions [Roy, S., Ghosh, A.K., "*Magnetic field profile in two dimensional superconducting networks below the critical temperature*", Third International Conference on Advanced Materials (ICAM 2019), Kottayam, Kerala, India, 9-11 August 2019]. Keeping with the 1D model, we consider both Rademacher and Gaussian distributions for spatial variations in pinning profile of the sample. Solving the critical state equation independently along both axes and integrating local fields along spatial extension of the sample and time period of the ac field, we calculate the magnetic susceptibility of the sample. Qualitative comparison of the change in imaginary part of susceptibility with temperature between the 1D and 2D models is undertaken. Peak temperatures show a similar trend of increase to higher values with decrease in grain radii. T_p = 36 and 22 for RD pinned 2D sample with R_g/d = 1x10^{-4} and 4x10^{-4} respectively and α_s =1x10^5. T_p also increases with increase in magnitude of pinning potential. Further, isotropic conditions along both axes are broken and calculations of local field and susceptibility are carried out on such samples [S. Roy et al. "*Complex susceptibility in Repetitive Gaussian and Rademacher pinned 2D samples with low anisotropy*", 2021, in preparation].

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