Demagnetization induced peak effect for a FeSeTe granular superconductor in ac magnetic field

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Abstract. The possible evidence of a peak effect in the temperature dependent magnetization and in the field dependent critical current density has been found for a FeSeTe superconducting granular sample in presence of an ac field. The existence of the peak effect has been confirmed by the numerical calculation of the inter- and intragranular magnetizations in presence of a demagnetization field with components at the third harmonic frequency generated by the sample magnetization. This suggests that the peak effect could be related to the flux dynamics inside the sample through the demagnetization field third harmonic.

1. Introduction

The critical current density is one of the most useful parameters to be applied to type II superconductors, which is typically estimated by performing the magnetic hysteresis loop in presence of a dc magnetic field at different temperatures [1,2], and within the Bean’s critical state model [3]. This allows constructing both the temperature and field dependence of the critical current density [3–5]. The peak effect is one of the most interesting phenomena, which can be observed in both high- and Fe-based superconductors, consisting in the anomalous increase of the critical current density with increasing the applied field due to the pinning changes [6–11]. Although it is typically detected from dc magnetic measurements, the ac magnetic complex susceptibility technique may be also useful since it allows exploring the magnetic response of the samples at short time scales [12–18]. In fact, several interpretations of the peak effect give to it a dynamical origin in the critical state of superconductors [8,10,13,19–23], and the critical state and its characteristic frequency dependent flux dynamical regimes are accessible by performing pulsed field measurements. In presence of an ac field, the critical current density increases before dropping to zero at the superconducting transition, which produces a sudden decrease in the in-phase magnetization $M_1'(T)$ (or in the corresponding susceptibility real part $\chi_1'(T)$). Moreover, depending on the pinning strength, the sample geometry and the applied field amplitude, a second dissipation peak can occur in the out-of-phase magnetization $M_2''(T)$ (or in the corresponding susceptibility real part $\chi_2''(T)$) [24–29].

In the present work, we report the analysis of the ac magnetization measurements as function of the temperature and of the field dependent critical current density of a FeSeTe superconducting granular sample. From the experimental magnetization the first harmonic components of the inter- and intragranular magnetizations have been numerically calculated by using a model proposed in our previous work [30,31] and taking into account the magnetic interaction in the intergranular regions by means of the demagnetization fields at both the fundamental and third harmonic frequencies. In particular, we will relate these fields to the existence of a peak effect in the critical current density extracted from the experimental magnetic curves.

2. Experimental results

The temperature $T$ dependent fundamental and higher harmonics of the time $t$ dependent magnetization $M$ of a FeSe$_{0.5}$Te$_{0.5}$ granular sample, of the same batch obtained starting from its basic compound FeSe [32,33], have been acquired in absence of dc magnetic fields and in presence of an ac
field $\mu_0 H_{ac} \sin(2\pi vt)$ ($v$-frequency) by means of the ac susceptibility technique. The first five nonzero in-phase and out-of-phase odd components $M_n'$ and $M_n''$ with $n = 1, 3, ..., 9$ were measured as function of the temperature, while zero even component were found as expected in absence of dc field [12,13]. The magnetic field amplitude and frequency were taken as $\mu_0 H_{ac} = 0.5, 1, 2, 4, 8, 12$ mT and $v = 107, 1077, 5385, 9693$ Hz. The field was applied perpendicular to the longest dimension of the sample which consisted of a rectangular prism.

The curves of the first harmonic components $M_1'(T)$, $M_1''(T)$ and of the third harmonic components $M_3'(T)$, $M_3''(T)$ of the sample magnetization are reported in the Fig. 1a-1b and Fig. 1c-1d, respectively, at different amplitudes $\mu_0 H_{ac}$ and at fixed frequency $v$ of the applied ac field. The curves of the higher harmonics components are not reported since they are at least one order of magnitude lower than the first and third ones, and then can be neglected in the aim of the investigation of the ac response of the sample. The curves of $M_1'(T)$ exhibit a large peak and a small peak at intermediate and high temperatures, respectively. At a first sight, one could ascribe these two magnetic contributions to the inter- and intragranular ac responses, respectively [12,13,34]. However, as shown in the inset of the Fig. 1b, both peaks shift to lower temperatures with the increase of the field, with almost the same trend, while the intergranular contribution is expected to be faster than the intragranular one due to the different strengths of the superconductivity in the corresponding volume fractions [12,13,34,35]. However, after a more precise analysis of the curves and of their temperature derivatives (not reported here), we have isolated an additional very slight peak at low temperatures. Since this peak shifts very fast when increasing the ac field amplitude, as shown in the inset of the Fig. 1b, we argue that it could be ascribed to the intergranular contribution, indicating a bad quality of the intergranular links of the sample which produces a high coherence of the superconducting transition inside the sample [12]. Within such interpretation the smaller peak near the transition temperature $T_c$ should be ascribed to the intragranular response and the second larger one at intermediate temperatures $T_p$ could be an additional effect.

![Figure 1](image)

**Figure 1.** (Left) Plots of the temperature dependent magnetization first harmonic (a) in-phase and (b) out-of-phase components measured on the FeSe$_{0.5}$Te$_{0.5}$ sample, at different amplitudes $\mu_0 H_{ac}$ and at fixed frequency $v$ of the applied ac field $H$. The vertical lines indicate (dotted) the intergranular $T^I$ and (dashed) the intragranular $T^G$ dissipation peaks temperatures, and (solid) the possible peak effect $T_p$ temperatures, and the inset is the plot of the field dependence of the peaks positions. (Right) Plot of the corresponding third harmonic curves with the inset showing the field dependent critical current density of the sample calculated from the $M(H)$ loops constructed by taking the magnetization curves of the (a,b,c,d) panels and the applied field $\mu_0 H_{ac} \sin(2\pi vt)$[3,4] ($H_p$ field of the peak effect).
In order to further analyze the experimental magnetization curves, the field dependent critical current density has been extracted from the curves of the magnetic hysteresis loops of the system constructed by taking the time dependent magnetization signal \( M(t, T) = \sum_{n=1,3} M_n(T, t) \) with \( M_n(T, t) = M_n^0(T) \sin(n\omega t) + M_n^0(T) \cos(n\omega t) \) (with \( \omega = 2\pi v \)), as function of the applied field \( \mu_0H_{ac} \sin(\omega t) \), at different temperatures. From these loops, within the Bean’s critical state model [3,4], the critical current density \( j_c \) as function of the applied field during an ac field cycle has been calculated as the difference between the demagnetization and magnetization branches of the loop normalized to a factor related to the geometry of the sample’s surface perpendicular to the applied field. The curve of \( j_c(H) \) at intermediate amplitude and frequency values of the applied ac field and at the corresponding temperature \( T_p \) of the possible peak effect in the Fig. 1b, is reported in the inset of the Fig. 1d. This curve clearly exhibits an increase of the current density with the increase of the field at intermediate values of the field, as expected in presence of a peak effect in the magnetic response of the sample. In order to identify the inter-and intragranular nature of the peak effect, the inter- (i) and intragranular (g) ac magnetization curves \( M_{1i}^g(T) \), \( M_{3i}^g(T) \) and ac susceptibility curves \( \chi_{1i}^g(T) \), \( \chi_{3i}^g(T) \) will be determined and analyzed in the following section.

3. Analysis and discussions of the fundamental magnetization

In order to investigate the actual origin of the peak effect appearing in the curves of the critical current density of the sample reported in the inset of the Fig. 1d, the fundamental magnetization curves \( M_{1i}^i(T) \) and \( M_{3i}^i(T) \) have been analyzed in the framework of a model for the description of the ac response of a granular system [30]. In fact, the inter- and intragranular magnetization and susceptibility curves have been calculated from the whole sample’s experimental curves, by numerically solving the equation (\( \mu_0 \) vacuum magnetic permeability)

\[
\mu_0M_n(t, T) \approx \frac{(1-f^g+D^i)\mu_0M_n^0(t, T)+(f^g+D^g)\mu_0M_n^0(t, T)}{1-D}, n = 1, 3.
\]

Here \( f^g \) is the granular volume fraction of the sample, \( D \) is the demagnetization factor for the whole sample geometry, while \( D^i \) and \( D^g \) are two effective inter- and intragranular demagnetization factors. Moreover, \( M_{1i}^i(T) \) and \( M_{3i}^i(T) \) are the inter- and intragranular magnetizations Fourier components

\[
\mu_0M_{1i}^g(t, T) = \text{Im} \left\{ \sum_{n=1,3} \frac{M_{1g}^0}{n} \left[ B_{1g}^i(t, T) \right]^n \right\},
\]

where \( \chi_{1i}^g \) are the susceptibilities harmonics, and the demagnetization effects due to the geometry of the whole sample and of the grains are taken into account within two effective magnetic fields \( B_{1i}^i(t, T) \) and \( B_{1g}^g(t, T) \) acting at the surfaces of the sample and of the grains, respectively. These are given by

\[
B_{1i}^i(t, T) = \mu_0H_{ac}e^{i\omega t} - D[\mu_0[M_1(T)e^{i\omega t} + iM_1(T)e^{-i\omega t}] + [M_3(T)e^{3i\omega t} + iM_3(T)e^{-3i\omega t}]],
\]

\[
B_{1g}^g(t, T) = \mu_0H_{ac}e^{i\omega t} + (1-D)[\mu_0[M_1(T)e^{i\omega t} + iM_1(T)e^{-i\omega t}] + [M_3(T)e^{3i\omega t} + iM_3(T)e^{-3i\omega t}]].
\]

It is worth noting that the first and the third harmonics of the sample magnetization \( M_1(t, T) \) and \( M_3(t, T) \) generate two demagnetization fields contributions at the fundamental frequency and two contributions at the third harmonic frequency. These fields at frequency \( \omega \) and \( 3\omega \) produce contributions in the fundamental magnetizations, named \( M_{11}^i(t, T) \) and \( M_{31}^i(t, T) \), respectively, for the inter- and intragranular volume fractions. The factor \( D \) can be taken from the literature for the considered sample geometry.

The inter- and the intragranular magnetization curves, in presence of the demagnetization field harmonics components at the fundamental frequency \( -D[M_1(T)e^{i\omega t} + iM_1(T)e^{-i\omega t}] \) and \( (1-D)[M_3(T)e^{i\omega t} + iM_3(T)e^{-i\omega t}] \) only and in presence of both the fundamental components and the components at the third harmonic frequency \( -D[M_3(T)e^{i\omega t} + iM_3(T)e^{-i\omega t}] \) and \( (1-D)[M_3(T)e^{i3\omega t} + iM_3(T)e^{-i3\omega t}] \).
$iM_0(T)e^{-i\omega t}$, have been numerically calculated from the self-consistent equations system of the Eq. (1), together with the Eq. (2) and (3a)-(3b). The corresponding susceptibilities $\chi_1(T)$, $\chi''_1(T)$ and $\chi''_1(T)$, have also been obtained within the calculation.

The curves of $M_{11}^{[1]}(T)$, $M_{11}^{[2]}(T)$ and $M_{11}^{[3]}(T)$ are shown in the Fig. 2a-2b and 2c-2d, respectively, together with the corresponding susceptibility curves. In these Fig., the in-phase magnetization curves $M_{11}^{[1]}(T)$ and $M_{11}^{[2]}(T)$ exhibit the typical behavior expected in absence of a peak effect in ac field, that is a negative peak due to the temperature dependence of the amplitudes $B^\theta(T)$ of the effective field acting at the surfaces of the grains which is shielded by the intergranular currents at lower temperatures. Moreover, two peaks appear in the corresponding out-of-phase curves $M_{11}^{[1]}(T)$ and $M_{11}^{[2]}(T)$, respectively, at the temperatures $T^R$ and $T^\theta$ individuated in the Fig. 1a and 1b.

![Figure 2](image-url)

Figure 2. Plots of the temperature dependent fundamental magnetization curves in presence of (left) the fundamental and (right) both the fundamental and the third harmonic demagnetization fields calculated within the model described in the previous section and in Ref.[30]. The (a,c) and the (b,d) panels are the in-phase and the out-of-phase components, respectively.

On the other hand, no effects are visible at the peak effect temperature $T_p$, showed in the curves of the Fig. 1a-1b and of the inset of the Fig. 1d, containing all the magnetization amounts acquired by the measuring system. Since these curves exhibit the magnetic response of the sample to the applied field and to the demagnetization field at both the fundamental and the higher frequencies, this suggests that the peak effect occurring in the magnetic response could be not visible in the curves of the fundamental magnetization components of the Fig. 2a-2b due to the fact that only the fundamental demagnetization field has been considered in their calculation. This kind of interpretation is confirmed from the inter- and the intragranular magnetization curves of the Fig. 2c-2d obtained when considering the demagnetization field third harmonics. Here it is clearly visible the existence of a drop in both the inter- and intragranular in-phase curves $M^I_{11}(T)$ and $M^\theta_{11}(T)$, near the corresponding transition temperatures $T^I$ and $T^\theta$, respectively. At these temperatures, a second peak is observed in the inter- and intragranular out-of-phase curves $M^I_{11}(T)$ and $M^\theta_{11}(T)$. Both these features of the in-phase and out-of-phase curves could be considered as the evidence, in presence of an ac field, of a peak effect in both the inter- and intragranular volume fractions. In this kind of interpretation, the intergranular peak effect could be covered in the curves of the whole sample magnetization of the Fig. 1a-1b, while the intragranular peak effect remains visible in the out-of-phase magnetization curves.
4. Conclusions

The fundamental harmonics components of the magnetizations of the inter- and intragranular volume fractions in a superconducting granular sample have been numerically extracted from the experimental whole sample magnetization as function of the temperature. The experimental curves indicate the existence of a peak effect in the critical current density of the sample, and the features of this phenomenon have been found in the separated inter- and intragranular magnetization components only when considering the existence of demagnetization fields components at the third harmonic frequency in addition to the fundamental harmonics components. These results suggest the third harmonic demagnetization field at the origin of the peak effect observed in the critical current density of the superconducting granular sample. This could be crucial since within the used model the demagnetization induced peak effect depends on the granularity of the system and then it could be controlled in the applications by means of the sample granular structure.

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