Depinning and vortex-glass-like transition in Nb with uncorrelated disorder

A. A. M. Oliveira a, *, P. N. Lisboa-Filho b, W. A. Ortiz a

a Grupo de Supercondutividade e Magnetismo, Departamento de Física, Universidade Federal de São Carlos, São Carlos, SP, Brazil

b Laboratório de Materiais Supercondutores, Departamento de Física, Universidade Estadual Paulista, Bauru, SP, Brazil

* ana@df.ufscar.br

Abstract. Studies of the third harmonic of the AC-susceptibility were conducted to detect the boundaries of the linear regime of the magnetic response of granular Nb samples. These studies reveal the extent of the region, on the phase diagram, where the magnetic response is linear, which corresponds to the disordered phase of Vortex Matter. The present work addresses the correlation between a linear response and experimental parameters such as the frequency and the amplitude of the excitation field. The order-disorder border has been extracted from the onset temperature of the third harmonic measured at low-frequencies and low-excitation fields in the presence of dc magnetic fields.

1. Introduction

Magnetic flux penetrates into a type II superconductor as quantized vortices, which combine to form Vortex Matter (VM). In a pristine material with no pinning centers, the vortices tend to form a regular mesh, known as the Abrikosov lattice. Actual specimens, however, always have inhomogeneities associated with defects and disorder, acting as flux pinning centers (PCs), which affect the order of the vortex lattice. A number of possible arrangements can exist for the vortex solid state. For example, when the density of defects is not too large, the distortions of the lattice will be less important, and the solid is known as a Bragg glass [1, 2]. In this phase, translational long range order is preserved and Bragg diffraction peaks are observed [3]. If the pinning centers are strong or if there is a large amount of them, the solid can no longer be regarded as a perfect lattice. In the presence of uncorrelated disorder, like impurities, the vortex lattice gives place to a vortex-glass state [4, 5]. A somewhat different situation occurs in the presence of correlated disorder, like in the case of columnar defects: for magnetic fields aligned to the defect, the solid is a Bose glass [6]. Thus, the properties of the vortex solid phase depend on the type and amount of disorder present in the system under study. Likewise, the border line between ordered and disordered vortex states also depends on the type and density of defects. The melting of the vortex-solid phase has been investigated by several techniques. In this paper, we determined the order-disorder transition (OD) of granular Nb samples employing the third harmonic of the AC-susceptibility technique, which allows one to detect changes between ordered and disordered regimes of VM.
2. Experimental Procedure

Three granular samples of Nb were employed in this experiment: powder (Sample I) and two pellets submitted to different pressures (Sample II – P ~ 6000 kgf/cm² and Sample III – P ~ 12000 kgf/cm²). The samples were fabricated from classified powder according to procedures especially optimized for our group [7, 8]. Nb powder was separated according to grain size, using a set of special sieves, resulting in grains with lateral dimensions ranging from 38 to 44 µm, and then submitted to controlled pressures to form a pellet. Third harmonic of the AC-susceptibility measurements were carried out in a Physical Properties Measurements System PPMS Model 6000 (Quantum Design). To identify the extension of the region of linear magnetic response, measurements of the amplitude of the first, \( \chi_1 \), and third, \( \chi_3 \), harmonics were taken as a function of temperature, at different values of the excitation field amplitude, \( h \), and frequency, \( f \). As an example, we present in Figure 1 measurements of \( \chi_1(T) \) and \( \chi_3(T) \) for the Samples I and II. It should be noticed the logarithmic vertical scale, which makes it possible to see the whole curve at a glance and facilitates discrimination between noise and a non-zero response. The last point belonging to the noise part of \( \chi_3 \), \( T_3^{\text{onset}} \), was chosen as the onset of the nonlinear response. In addition, this figure illustrates that the onset temperature of \( \chi_1 \), \( T_1^{\text{onset}} = T_c \), is higher than \( T_3^{\text{onset}} \), suggesting that for \( T_3^{\text{onset}} < T < T_1^{\text{onset}} \), the magnetic response is linear, i.e., \( \chi_1 \neq 0 \) and \( \chi_3 = 0 \). Here, \( T_c \) is the critical temperature of the sample.

![Figure 1: Temperature dependence of the amplitudes of first and third harmonics of the AC-susceptibility for Samples I (a) and II (b), respectively. These results were taken with Sample I submitted to the remnant magnetic field of the superconducting magnet of the experimental station, on the order of a few Oersted, and Sample II subjected to a field of 100 Oe.](image)

3. Results and discussion

3.1. Dependence of \( T_3^{\text{onset}} \) with \( h \) and \( f \)

A systematic study of \( \chi_3 \) was conducted to analyze the extension of the region of the linear magnetic response, i.e., the dependence of \( T_3^{\text{onset}} \), with the values of the experimental parameters; \( h \) and \( f \). Figure 2 shows the dependence of \( T_3^{\text{onset}} \) on \( h \) for three different values of frequency. For Sample I, Figure 2 (a), the data indicate that for 10 and 100 Hz, \( T_3^{\text{onset}} \) tends asymptotically to a limiting value when \( h \leq 70 \) mOe, while for 1000 Hz, \( T_3^{\text{onset}} \) approaches to the same value only for \( h \leq 6 \) mOe. Similarly, the data obtained for Sample II, Figure 2 (b), indicate that for 10, 100 and 1000 Hz, \( T_3^{\text{onset}} \) tends to the same temperature value when \( h \leq 100 \) mOe, \( h \leq 50 \) mOe and \( h \leq 30 \) mOe, respectively.
The frequency dependence of $T_3^{\text{onset}}$, Figure 3, was obtained by performing measurements of $\chi_3(T)$ for several values of $f$, with a fixed value of $h = 30$ mOe. The value of $h$ was chosen to ensure operation at the asymptotic regime at all frequencies. Figure 2 indicates that for $h < 30$ mOe (shadow region), $T_3^{\text{onset}}$ already reached a limiting value, except for the measure accomplished on Sample I at 1000 Hz, suggesting that even for low amplitudes, the response function of the system can depend of the frequency of the excitation field.

In Figure 3, the behavior of $T_3^{\text{onset}}(f)$ was analyzed in accordance with the vortex-glass approach [4, 5], where $T_3^{\text{onset}}$ was defined, for the three-dimensional case (3D) and small $f$, as

$$T_3^{\text{onset}}(f) = T_{OD} + A f^{\delta} \quad (1)$$

Here, $\delta$ is given by $1/(z-1)v$, with $z$ the dynamical and $v$ the correlation-length critical exponents, respectively, associated with the vortex-liquid to vortex-glass transition, and $T_{OD}$ is the threshold temperature of disorder of VM. The solid line is a fit of equation (1) to the $T_3^{\text{onset}}(f)$ data, for which the parameters $\delta$ and $T_{OD}$ were determined.

Figure 3: Dependence of $T_3^{\text{onset}}$ with $f$ for Samples I (a) and II (b), respectively. The amplitude of the excitation field was fixed at 30 mOe.
3.2. H-T Phase Diagram

Results presented in the previous section revealed that $T_{3\text{onset}}$ can be adopted as a good approach for $T_{OD}$, provided that measurements of $\chi_3(T)$ are accomplished at sufficiently low frequencies and amplitudes. This methodology was employed to determine a boundary in the H-T phase diagram that defines the ordered regime of VM, a drawing of which is shown in Figure 4. Each point of the OD-line was obtained from the measurements of $\chi_3$ as a function of temperature, at $h = 30$ mOe and $f = 100$ Hz.

Although the OD–borders determined for the three samples are quite similar, one must consider that in Sample I the PCs are intragranular defects, whereas the other two specimens have also weak-links (WLs) between adjacent grains. It is apparent that $H_{OD}$ is lower for Sample I which means that, for a certain value of the applied field, its magnetic response is nonlinear in a smaller range of temperatures, consistently with the notion that the WLs are more efficient in pinning vortices than the intragranular defects.

![Figure 4: $H_{OD}$ for the studied Nb samples. The lower panel is an amplification of the low-field region for Sample II. The upper panel shows the OD–lines collapsed into one curve, corresponding to the high-field region. In this case both axes are in logarithmic scales.](image)

We have attempted to adjust the experimental points to some of the existing models, concluding that the OD–line has to be divided into two different regimes, as is made evident by the lower and upper panels of Figure 4. The low-temperature region is well fitted by the 3D vortex-glass model, which gives the melting field

$$H_m = H_0 (1-t)^n$$

(2)

where $n$ is a fitting parameter and $t = T_{3\text{onset}}^0(0)$. However, this model is clearly not appropriate for the low-field region, which can be reasonably fitted using a model developed by Lopatin and Vinokur [9]. It predicts that the depinning of vortices, induced through the increase of the temperature, anticipates the melting point which, in the present case, would be the disorder limit. As a result the frontier line exhibits a kink, signaling a change of regime (depinning crossover). This depinning originates an OD–line which, in the presence of columnar defects, can be described as...
\[ H_{OD} \propto \left[ T^3_{3\text{onset}}(H) \right]^2 \exp[-T^3_{3\text{onset}}(H)/T_0] \]  
(3)
where \( T_0 \) is an effective temperature to be adjusted.

In the main panel of Figure 4, the dashed lines are fittings of the data with equation 2, whereas on the lower panel, the solid line was adjusted with equation (3). The fitting parameters for the three samples were: Sample I – \( T^3_{3\text{onset}}(0) = (8.34 \pm 0.05) \) K, \( n = (1.13 \pm 0.06) \), \( H_0 = (20738 \pm 1164) \) T, and \( T_0 = (0.080 \pm 0.003) \) K; Sample II – \( T^3_{3\text{onset}}(0) = (8.21 \pm 0.04) \) K, \( n = (1.10 \pm 0.02) \), \( H_0 = (29035 \pm 427) \) T, and \( T_0 = (0.23 \pm 0.02) \) K; Sample III – \( T^3_{3\text{onset}}(0) = (8.09 \pm 0.09) \) K, \( n = (1.02 \pm 0.06) \), \( H_0 = (31318 \pm 1328) \) T and \( T_0 = (0.19 \pm 0.01) \) K. Using these adjusted parameters and rewriting the equation 2 as:

\[ h = (1-t)^n \]  
(4)
where \( h = H/H_0 \), the OD–lines can be viewed as a universal two-regime frontier having a material-dependent, lower-temperature, vortex-glass behavior, and a processing-dependent, higher-temperature, depinning crossover. One can collapse data – privilege to one or the other regime depends on the choice of the variables – as shown on the upper panel of Figure 4. It becomes clear that, for all samples, the low-temperature data obey equation 4 (vortex-glass), whereas for higher temperatures they deviate where the depinning crossover sets in.

4. Final remarks
We have employed the third harmonic of the AC-susceptibility to determine the order-disorder transition of Vortex Matter of granular Nb samples. Our results reveal that the order-disorder line exhibits a two-regime behavior: at lower temperatures, the ordered phase melts as a vortex-glass system, whereas higher temperatures induce depinning which, in turn, anticipates disorder.

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References
[1] T. Giamarchi and P. Le Doussal, Phys. Rev. B. 52 (1995) 1242
[2] T. Giamarchi and P. Le Doussal, Phys. Rev. B. 55 (1997) 6577
[3] T. Klein et al., Nature 413 (2001) 404
[4] M. P. A. Fisher, Phys. Rev. Lett. 62 (1989) 1415
[5] D. S. Fisher et al., Phys. Rev. B 43 (1991) 130
[6] D. R. Nelson and V. M. Vinokur, Phys. Rev. B. 48 (1993) 13060
[7] W. A. C. Passos, Ph. D. thesis, Grupo de Supercondutividade e Magnetismo, PPG-FIS/UFSCar, 2001
[8] W. A. C. Passos et al., Physica C 354, (2001) 189
[9] A. V. Lopatin and V. M. Vinokur, Phys. Rev. Lett. 92 (2004) 067008