Critical state models for a granular ferromagnetic superconductor

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Abstract

Measurements of the magnetic moment M as a function of the magnetic field B can be used to extract information about the penetration behaviour of the magnetic field in a superconducting sample. In granular superconductors the response to an applied a.c. field is governed by both intra- and intergranular shielding currents. We have employed low field a.c. susceptibility measurements to investigate the magnetic properties of a polycrystalline $RuSr_2GdCu_2O_8$ weak ferromagnet in its superconducting state. For fields below $\simeq 10\,G$ the results are consistent with the Bean critical state model. For $B > 10\,G$ the Kim model is more suitable for the description of the sample's properties.

Key words: superconductivity; magnetism; $RuSr_2GdCu_2O_8$;

1. Introduction

Granular superconductors can be modeled as a two-component system, the grains and the contacts between them [1]. The parameters of the Josephson-effect based coupling between the grains may be determined from the magnetic field dependent transport and screening properties. Several models are available for this purpose. The simplest one is the Bean critical state model in which current density is assumed to be independent of the local magnetic field, In this paper we investigate the applicability of this model for $RuSr_2GdCu_2O_8$ (Ru-1212). This compound becomes superconducting with a critical temperature $T_s \simeq 40\,K$ well below the transition into a (weakly) ferromagnetic state at $T_m \simeq 135\,K$ [2].

2. Experimental

Polycrystalline samples of Ru-1212 were prepared following a two-step procedure proposed by Bauernfeind *et al.* [2]. First, Sr_2GdRuO_6 (Sr-2116) was prepared from stoichiometric quantities of RuO_2, Gd_2O_3 and $SrCO_3$. The mixed powders were ground, calcined at 950 °C in air, reground, milled, pressed into pellets and fired for 16 h at 1250 °C in air. In a second step, the obtained Sr-2116 was mixed with CuO and the mixture was ground, milled, pressed into pellets and fired for 720 hours at 1060 °C in flowing oxygen.

X-ray powder diffraction showed that the produced samples were single phase. From resistivity and a.c. susceptibility measurements we determined a superconducting transition temperature of $T_s = 35\,K$.

In order to avoid the problems related with the SQUID magnetometry of Ru-1212 [3] a home made a.c. susceptometer was used for the measurements, where the sample was kept stationary within the pickup coil system, while the primary field was created by a coil made from normal conducting Cu-wire.

3. Results and discussion

The strong depression of T_s with a.c. field amplitude observed in susceptibility measurements is indicative of granular superconductivity with a low intergranular critical current density [2]. In Fig. 1, we present hysteresis curves measured in the superconducting state ($T < 35\,K$) of our Ru-1212 sample with a field am-

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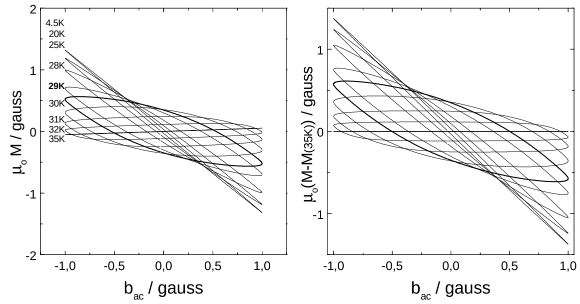

Fig. 1. Hysteresis loops of Ru-1212 measured with a field amplitude of 1 G ($f = 22.22$ Hz) (left) and corrected for the paramagnetic background contribution (right).

plitude of 1 G. At 35 K, the loop is nearly closed and corresponds to the magnetic background signal due to the Gd and Ru moments. The dissipation reaches its maximum around 29 K, while at lower temperatures the shielding increases and the slope becomes more and more diamagnetic. In the right panel of Fig. 1, we present the hysteresis loops after correction for the paramagnetic background signal. Above the *penetration temperature* of 29 K, at which the field amplitude corresponds to the *penetration field*, the loops follow very well the flat behaviour expected from the Bean critical state model [4].

The intergranular supercurrents will be suppressed when the critical field B_{cJ} of these Josephson contacts is reached. According to Tinkham [5], above B_{cJ} a field dependence of the intergranular critical current density appears so that the Bean model is no longer applicable. B_{cJ} is a material parameter which is independent of the intrinsinc properties of the superconducting phase and depends only on the average grain size α, with $B_{\mathrm{cJ}} = \Phi_0/\alpha^2$, where Φ_0 is the flux quantum. B_{cJ} should not be considered a limit above which no intergranular superconductivity can exist. Rather, it marks the crossover between the region of field independent critical current density (Bean region) and the region where the critical current density depends strongly on the applied field.

For field amplitudes above 8 G, the shape of the hysteresis loops as shown in Fig. 2 indeed deviates from that predicted by the Bean model. In this region of field dependent critical current density, more complex critical state models are required to describe the behaviour of the sample. Our measurements (Fig. 2) are in qualitative agreement with the Kim model [4]. The field B_{cJ} is in the order of 10 G from which we derive a mean grain size $\alpha \simeq 2\,\mu$m in agreement with our electron microscopy data [2]. The observed transition from a field independent (Bean-like) to a field dependent (Kim-like) behaviour in the region mentioned above represents a confirmation of the Clem-Tinkham model for the intergranular critical current density.

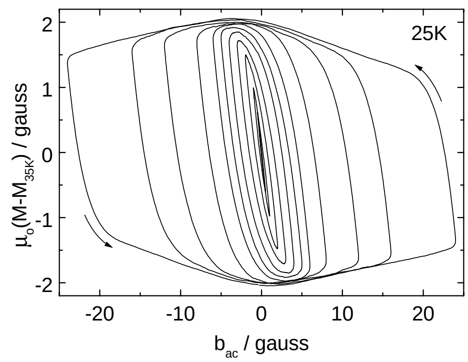

Fig. 2. Corrected hysteresis loops for field amplitudes between 0.25 and 24 G. Above about 8 G, the curves start to deviate from the shape predicted by the Bean model and show a behaviour which is qualitatively consistent with the Kim model (field dependent critical current density).

4. Summary

Low field a.c. susceptometry has been employed for the investigation of the magnetic properties of Ru-1212 in its superconducting state. For small field changes, the Bean critical state model appears to be adequate for the description of our results. Nevertheless, for field changes above 10 G, more involved models have to be employed. In this field range our measurements are in qualitative agreement with the Kim critical state model.

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