Flux Creep in the Quasi-1D Superconducting Carbide Sc_3CoC_4

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Abstract. The superconducting flux dynamic of the transition metal carbide Sc_3CoC_4 which exhibits a quasi-one-dimensional structure is studied. Besides zero-field-cooling (zfc), field-cooling (fc) and magnetization measurements, especially flux creep relaxation experiments are performed. The relaxation rates $S = \mathrm{d}M/\mathrm{dln}t$ are determined at selected temperatures below the transition temperature T_c in two magnetic fields of 50 Oe and 100 Oe just above H_{c1}. The resulting supercurrent dependence on the mean activation energy is analyzed according to the collective pinning theory which predicts $U \sim ((j/j_c)^{-\mu} - 1)$. The calculated μ-values differ in the high and low temperature region. The μ-values below about 2.5 K are ≈ 0.5-0.68 depending slightly on the applied magnetic field whereas at higher temperatures the μ-values are ≈ 0.22-0.34. These results might indicate a transition between different types of vortex pinning around 2.5 K changing from single vortex creep at higher temperatures to collective creep of vortex bundles at lower temperatures.

1. Introduction

Recently, superconductivity in the transition metal carbide Sc_3CoC_4 was reported [1]. In spite of the close structural relationship of the isotypic Sc_3TC_4 carbides (T = Fe, Co, Ni) consisting of quasi one-dimensional $[TC_4]$ chains embedded in a scandium matrix only the Co system shows superconductivity. It can be regarded as a model system to study the rare phenomenon of quasi one-dimensional superconductivity. Scheidt et al. [2] already determined detailed superconducting properties like critical quantities, magnetization and specific heat behavior in connection with structural features indicating some characteristics of low dimensional superconductivity. In order to obtain further information about superconducting properties detailed measurements of the flux creep relaxation are performed. The results are discussed within the scope of a thermally activated flux creep model based on the Anderson-Kim theory [3] which is frequently applied to conventional type-II [4] as well as to high-T_c superconductors [5, 6].

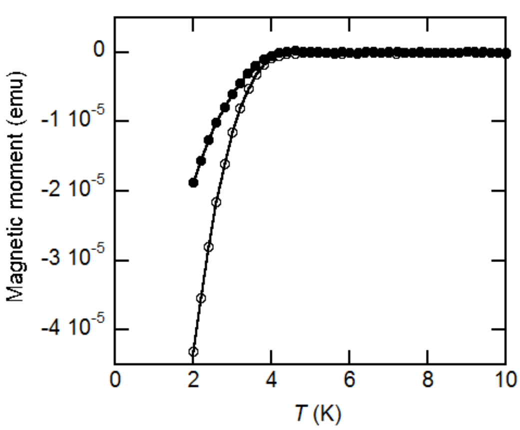
2. Experimental

Powder samples of Sc_3CoC_4 are prepared following the procedure described in Ref. [7]. Using a sample with a mass of 120.4 mg zero field cooled (zfc), field cooled (fc), magnetization, and flux creep relaxation measurements are performed by means of a commercially available magnetometer (MPMS, Quantum Design Inc.).

3. Results and discussion

Fig. 1 shows the zfc-fc transition curves for a magnetic field of 100 Oe**.** The paramagnetic contribution due to this field obtained from the behavior above T_c, is subtracted. The onset transition temperature in this field is T_c = 4.4 K.

An example of a magnetization loop is shown in Fig. 2. The first minimum at T = 1.8 K occurs at about H = 40 Oe, the values at higher temperatures are slightly smaller. Accordingly the relaxation measurements are started after applying higher field values, in our case H = 50 Oe and H = 100 Oe, respectively.



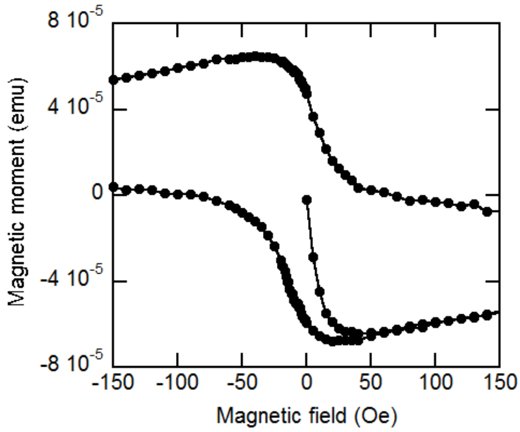
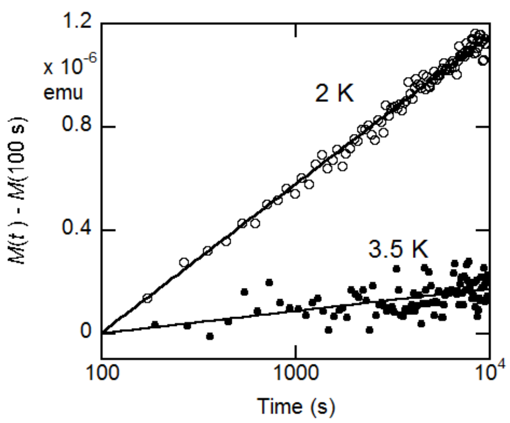


Figure 1. Zero field cooled (zfc, open symbols) and field cooled (fc, closed symbols) curves for a magnetic field of H = 100 Oe. The paramagnetic contribution due to this field is subtracted.

Figure 2. Central part of the magnetization loop at T = 1.8 K. The paramagnetic contribution is subtracted. Relaxation measurements are performed at fields of H = 50 Oe and H = 100 Oe.

The results of the relaxation measurements are summarized in Figs. 3 - 6. Two examples of relaxation curves obtained at T = 2 K and T = 3.5 K after application of a magnetic field of H = 100 Oe are shown in Fig. 3. At both temperatures, according to the Anderson-Kim theory [3], a logarithmic decay is observed. In comparison to the 2 K curve, the slope of the relaxation curve at higher temperature is considerably reduced. Such a behavior is also found in further measurements, performed at selected temperatures T = 1.8 K, 2.5 K, and 3.0 K. The resulting temperature dependence of the relaxation rates $S = dM/d\ln t$ for the applied magnetic field values H = 50 Oe and H = 100 Oe are plotted in Fig. 4. The curves increase continuously from the transition temperature T_c = 4.4 K down to T = 1.8 K. The reduced relaxation rate at 1.8 K and 50 Oe might be due to the small magnetic field value just above H_{C1}. However, it is obvious that the relaxation behavior differs in the high and low temperature region. For 100 Oe the two low temperature rates are rather high compared to those at higher temperatures. The rate at 2.5 K corresponds more to those at 3 K and 3.5 K. For 50 Oe, however, the rate at 2.5 K corresponds more to the low temperature values. This might be a first hint



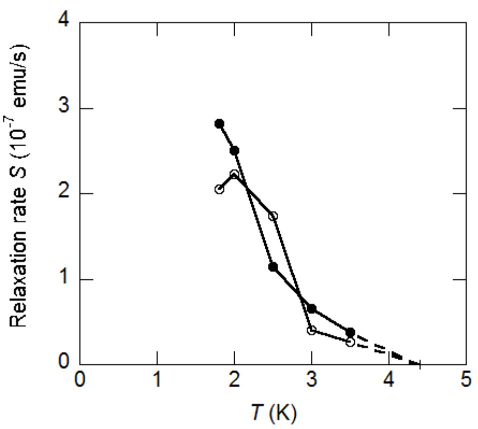


Figure 3. Relaxation curves of the magnetic moment recorded at T = 2 K and T = 3.5 K after applying a magnetic field of H = 100 Oe. The curves follow logarithmic time dependence (solid lines).

Figure 4. Temperature dependence of the relaxation rate $S = dM/d\ln t$ after application of a magnetic field of H = 50 Oe (open symbols) and 100 Oe (closed symbols)

for a transition between different types of vortex pinning around 2.5 K in the field region between 50 and 100 Oe.

Such a transition in the pinning behavior is supported by further analysis of the relaxation measurements according to the collective pinning theory [8]. Following a method proposed by Maley et al. [9], the relaxation at different temperatures leads to a consistent plot of the activation energy U (Figs. 5 and 6). It is based on the rate equation $\mathrm{d}M/\mathrm{d}t \sim \exp(-U/k_{\mathrm{B}}T)$, leading to $U = k_{\mathrm{B}}T(c - \ln(\mathrm{d}M/\mathrm{d}t))$. Here, c is used as fit parameter, yielding a smooth dependence of U vs. M. Since M is proportional to the superconducting current density, j, at least the functional form of $U(j)$ can be determined. In our case, this leads to a power law according to the collective pinning theory, which generally predicts $U \sim ((j/j_{\mathrm{c}})^{-\mu} - 1)$ (solid lines in Figs. 5 and 6); j_{c} is the critical current density and μ is a critical exponent that depends on dimensionality and effective bundle size of the vortex assembly.

As can be seen in Fig. 5, two μ-values result for a starting field of 100 Oe: $\mu = 0.68$ for lower temperatures and $\mu = 0.34$ for higher temperatures. Similar μ-values result for a starting field of 50 Oe (Fig. 6): $\mu = 0.5$ for lower temperatures and $\mu = 0.22$ for higher temperatures. The difference is that the behavior at 2.5 K for the starting field of 100 Oe again corresponds to the higher temperature region and can be described by the same μ-value belonging to 3 K and 3.5 K whereas for 50 Oe it changes to the low temperature μ-value belonging to 2 K and 1.8 K. This means that in the H-T-diagram a borderline between different pinning mechanisms just runs between 2 K and 3 K and between 50 Oe and 100 Oe. At higher fields and temperatures the lower μ-values are close to theoretical values for single vortex creep, $\mu = 0.18$ - 0.25 whereas in the low field and temperature region they correspond to those for creep of vortex bundles or Bragg glass behavior, $\mu = 0.5$ - 0.78 [10].

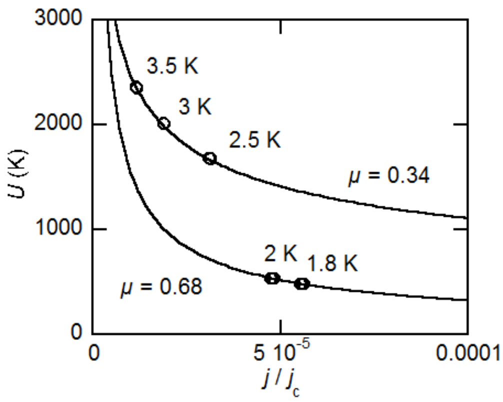


Figure 5. Mean activation energy as a function of supercurrent density normalized to the critical current density for a magnetic field of $H = 100$ Oe applied after zero field cooling

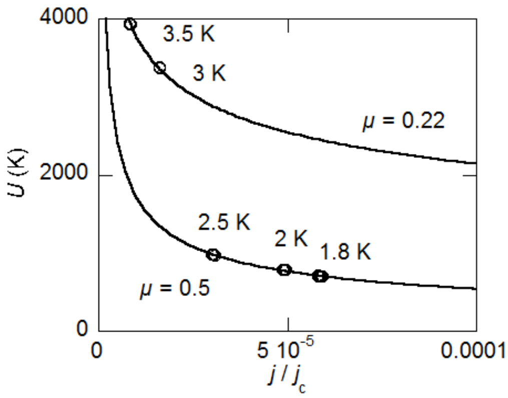


Figure 6. The same plot as in Figure 5 for a magnetic field of $H = 50$ Oe applied after zero field cooling

4. Conclusions

The analysis of flux relaxation measurements below the irreversibility line of the quasi one-dimensional (1D) superconductor Sc_3CoC_4 shows a different behavior at higher and lower temperatures. The pinning mechanism changes at about 2.5 K, dominated by single vortex flux creep above this temperature and vortex bundle flux creep below 2.5 K. The origin of this behavior might be connected with a transition in the type of superconductivity, changing for instance from surface to volume superconductivity with decreasing temperature. This might correspond with specific heat measurements which exhibit a peak just at 2.5 K [2] obviously indicating the formation of full volume superconductivity.

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