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Magnetic relaxation and lower critical field in MgB_2 wires

Y Feng[1,4], G Yan[1], Y Zhao[2], A K Pradhan[3], C F Liu[1], P X Zhang[1] and L Zhou[1]

[1] Northwest Institute for Nonferrous Metal Research, PO Box 51, Xi'an 710016, People's Republic of China
[2] School of Materials Science and Engineering, University of New South Wales, Sydney, NSW 2052, Australia
[3] Jesse W Beams Laboratory, University of Virginia, Charlottesville, VA 22901, USA

E-mail: yfeng@c-nin.com

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Abstract
Magnetic relaxation behaviour, critical current density J_c and lower critical field H_{c1} have been investigated in MgB_2/Ta/Cu wires. It is found that J_c and H_{c1} decrease linearly with temperature in the whole temperature region below T_c. The relaxation rate is very small and has a weak temperature dependence compared to high-T_c superconductors. Also, the pinning potential is much larger and the temperature and field dependences of the pinning potential are briefly discussed.

1. Introduction

The discovery of the new superconductor MgB_2, with a critical temperature T_c close to 40 K, has generated a lot of interest in the field of superconductivity due to its high T_c and good superconducting properties [1]. The transition temperature of MgB_2 is much higher than Nb_3Ge (by almost a factor of two), having the highest T_c in conventional superconductors. Some work has been done recently, including the observation of an isotope effect and band structure studies, which suggest that MgB_2 is a conventional phonon-mediated BCS superconductor [2, 3]. The advantage of MgB_2 is its applications in a higher-temperature region (20–30 K) due to its high T_c, low cost and absence of a weak link, where conventional superconductors cannot play a role due to their low T_cs. Also, a high upper critical field of 29–39 T has been reported in this material [4]. Recently, a very high J_c of 1.2×10^7 A cm^{-2} at 4.2 K at zero field was obtained in the *in situ* epitaxial MgB_2 thin film, suggesting that MgB_2 can reach extremely high intrinsic J_c [5]. These results indicate that MgB_2 may be the most promising compound for large-scale applications. Therefore, many groups are fabricating

[4] Author to whom any correspondence should be addressed.

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MgB_2 wires and tapes with high performance by using different metal sheaths. Canfield *et al* [6] fabricated high-density MgB_2 wires (160 μm in diameter) through the exposure of boron filaments to Mg vapour. Also, the recent reports on the preparation of MgB_2 wires by powder-in-tube (PIT) using either Ag or Cu sheaths and MgB_2 strands by filling Nb-lined monel tubes with commercial MgB_2 powders were the first steps to putting MgB_2 superconductors into applications [7, 8]. By using Cu as a sheath, a transport J_c of 50 000 A cm^{-2} at 15 K in a self-field was obtained in MgB_2 wires. For the non-sintered MgB_2/Ni tape, J_c reached around 10^5 A cm^{-2} at 4.2 K in a self-field [8]. Recently, Wang *et al* [9] reported their results on an Fe-clad MgB_2 wire, in which J_c achieved 4.2×10^5 A cm^{-2} at 4.2 K in a self-field. J_c is further improved to 1.7×10^4 A cm^{-2} in 1 T at 29.5 K and at 33 K in a self-field [10]. Also, transport J_c of 8700 and 55 830 A cm^{-2} at 4.2 K in a self-field were measured for Cu- and Fe/Cu-sheathed MgB_2 square wires, respectively, by using commercial MgB_2 powder [11]. On the other hand, another important feature that should be considered is the magnetic relaxation behaviour of MgB_2 superconductors. It is well known that a rapid decay of critical currents was often observed in high temperature superconductors (HTSC), which hampers its applications. To date, there are almost no reports on the magnetic relaxation behaviour of MgB_2 wires and tapes. In this paper, we present experimental results on the temperature dependence of J_c, magnetic relaxation behaviour and the field dependence of the lower critical field H_{c1} in MgB_2/Ta/Cu wires. Our data indicate that J_c and H_{c1} decrease linearly with temperature and that the relaxation rate is very small compared to high-T_c superconductors.

2. Experimental details

Single filamentary MgB_2/Cu composite wires with Ta as a buffer layer were fabricated using the *in situ* powder-in-tube process. Mg powder and amorphous B powder were used as starting materials in an atomic ratio of Mg:B = 1:2. A proportion of 5% extra Mg was added to compensate the loss of magnesium at high temperature. A detailed description of this process can be found elsewhere [12]. Finally, the wires were sintered at 600–900 °C for 2 h in argon at ambient pressure.

The dc magnetization was performed using a SQUID magnetometer. All the magnetization measurements were measured by first cooling the sample in zero field and then applying a field to begin the measurement. The field was applied perpendicular to the axis of the sample. After it finished at a given temperature, the field was set to zero and the temperature was warmed to 50 K to completely remove the trapped field inside the sample. The phase composition was analysed by x-ray diffraction measurements. A critical temperature T_c of 38.4 K with a sharp transition width of 0.6 K was observed from the magnetization measurements in the sample.

3. Results and discussion

X-ray diffraction patterns for the MgB_2/Ta/Cu wires are given in figure 1. The line-widths of the peaks are sharp, indicating that the sample exhibits good crystallinity. As seen in figure 1, the MgB_2 grains are not well textured. Also, no MgB_4 phase is found in the sample, which has a negative effect on the superconducting properties of MgB_2 due to its large mismatch in the crystal structure. In addition, only a few MgO phases can be observed in the sample.

Figure 2 shows the temperature dependence of the magnetic J_c at various fields for MgB_2/Ta/Cu wire. The J_c values are calculated from the magnetization curves using Bean's model of $J_c = 30\Delta M/d$, where d is the diameter of the sample and ΔM is the width of the magnetic hysteresis loops. It can be observed that J_c is relatively high around 10^5 A cm^{-2} at 5 K in a self-field and J_c decreases quickly as temperature increases. Interestingly, the

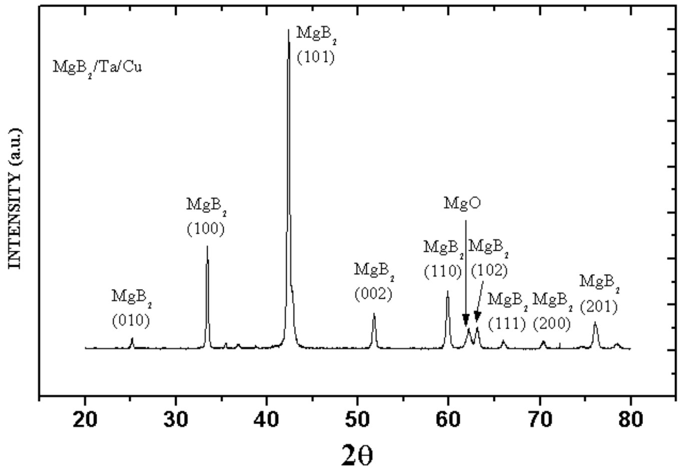

Figure 1. An x-ray diffraction pattern of the MgB_2/Ta/Cu wire. No MgB_4 is observed and only a few MgO phases exists.

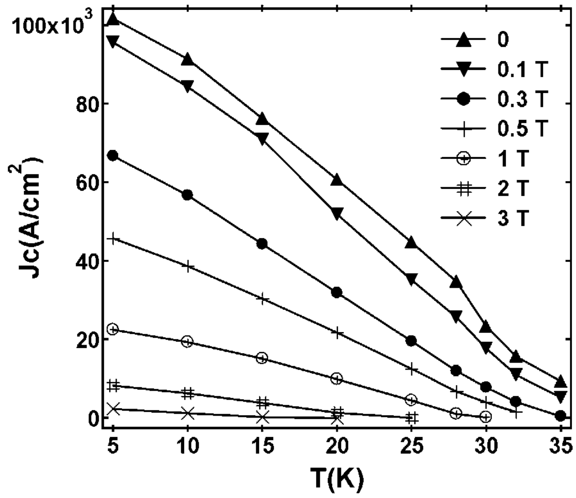

Figure 2. The critical current density as a function of temperature in various fields from 0.1 to 3 T. It is observed that J_c decreases with temperature almost linearly.

sample exhibits a simple temperature dependence, where J_c drops linearly with temperature at various fields. Similar behaviour was also found in the MgB_2 bulk samples [13]. In high-T_c superconductors, J_c often decreases with temperature according to a quasi-exponential law, which may be related to the large thermally activated flux creep. Therefore, it can be assumed that the thermal flux creep is not serious in MgB_2 superconductors.

The decay of normalized magnetization with time t was measured for the MgB_2/Ta/Cu wires using the SQUID magnetometer, and figure 3 shows the results. It can be observed that the normalized magnetization exhibits the linear decay of $\ln t$ at various temperatures and fields, indicating that this behaviour follows the Anderson–Kim model. The decay rate S was calculated from the equation $S = -\mathrm{d}\ln M/\mathrm{d}\ln t$. Figure 4 presents the decay rate as a function of field at 20 and 10 K and as a function of temperature at 0 and 0.5 T. The relaxation rate is very

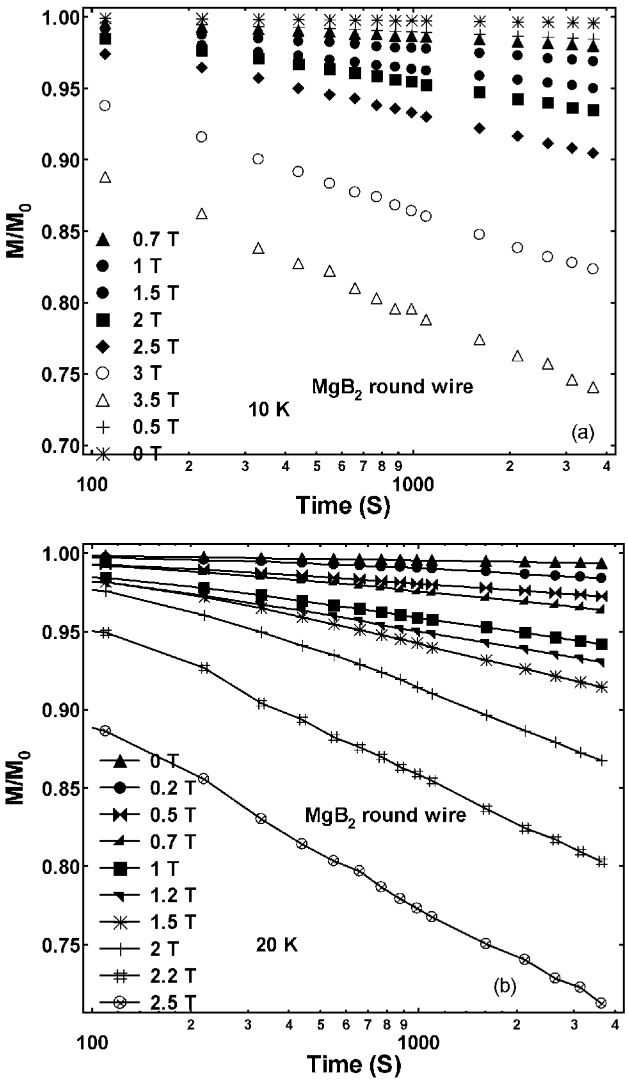

Figure 3. The time dependence of the normalized magnetization at (a) 10 K and (b) 20 K for MgB_2/Ta/Cu wires. A good linear relationship between the normalized magnetization and $\ln t$ is found, suggesting that the Anderson–Kim model is effective.

small, just around 0.086% at 5 K in 0 T. When the field increases to 0.5 T, S just reaches 0.003, being the same as the MgB_2 bulk sample [13, 14]. This value is an order of magnitude lower than that of HTSC. Furthermore, the relaxation rate shows a very weak temperature dependence in the measured temperature range. At 0.5 T, S increases from 0.003 at 5 K to 0.008 at 25 K. As described by Thompson *et al* [13], the exponent n of the electric field $E = E_0(J/J_0)^n$ is simply estimated by $(n-1) = 1/S$, where J is the current density. This will lead to an n value of around 300, corresponding to very steep curves in transport I–V characteristic. On the other hand, the relaxation rate increases slowly with field and may be high at a higher field, as observed in figure 4. For example, at 20 K, S increases from 0.0046 at 0.2 T to 0.062 at 2.5 T. The very small relaxation rate and weak temperature dependence may be related to the strong

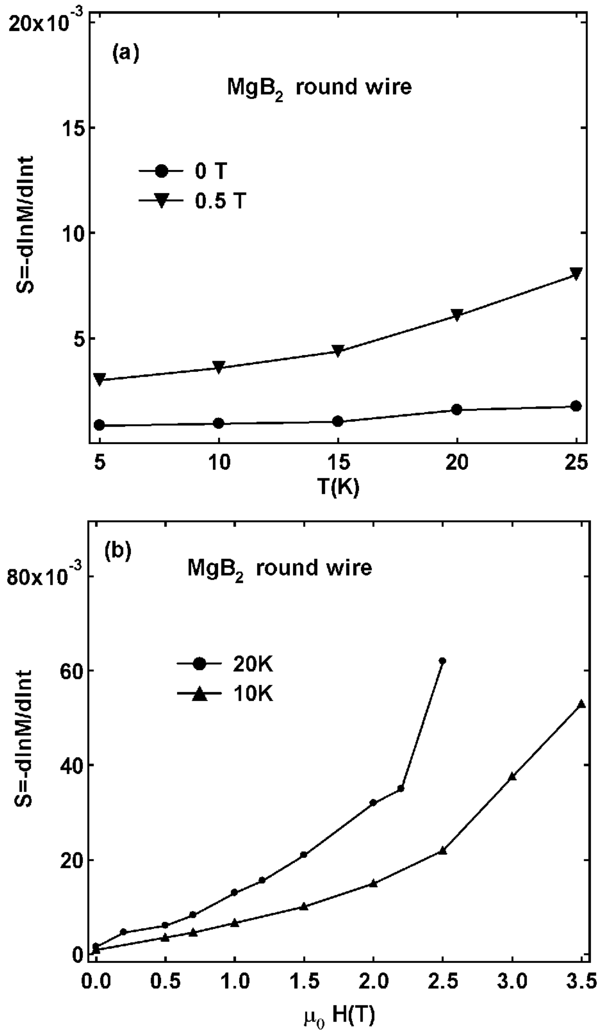

Figure 4. The relaxation rate as a function of temperature at (a) 0 and 0.5 T and (b) as a function of field at 10 and 20 K.

pinning barrier. The pinning potential U_0 of the sample can be calculated from the expression based on the Anderson–Kim model of $U_0 = -kT/S$. In figure 5, we present U_0 as a function of field and temperature. U_0 does not change with temperature monotonically, while it decays monotonically with field. It can be observed that the pinning potential at 0 T is much higher than that at 0.5 T at various temperatures. However, U_0 is almost the same at 10 and 20 K in high fields above 1 T. On the other hand, the pinning potential of the new superconductor is very large compared to HTSC. It is concluded that the intrinsic pinning energy is very high and that the pinning well of MgB_2 superconductors is so deep that the thermal activation and fluctuation has a trivial effect [15, 16].

Figure 6 shows the field dependence of magnetization at various temperatures for MgB_2/Ta/Cu wires. It is evident that all the curves exhibit the common linear field dependence of magnetization induced by the Meissner effect at low fields. The linear field dependence of magnetization is observed in fields below 400 Oe at 5 K. The lower critical field H_{c1} is

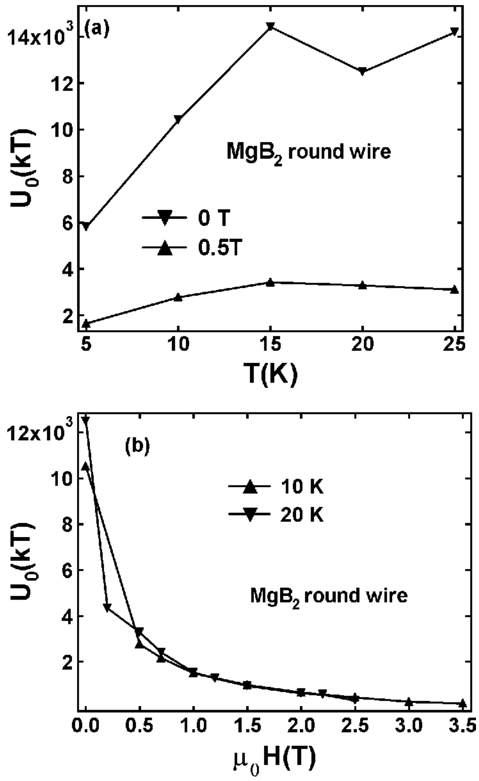

Figure 5. The pinning potential U_0 versus temperature at (a) 0 and 0.5 T and (b) versus field at 10 and 20 K.

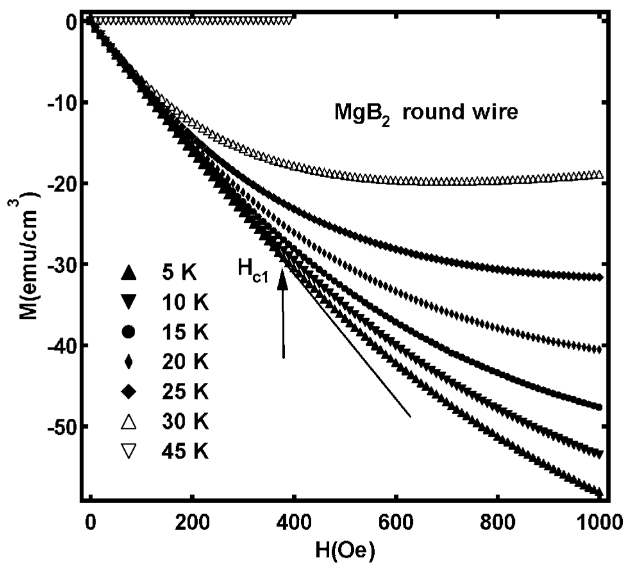

Figure 6. The field dependence of magnetization at various temperatures for MgB_2/Ta/Cu wire. It is found that the initial slope of all the curves is the same.

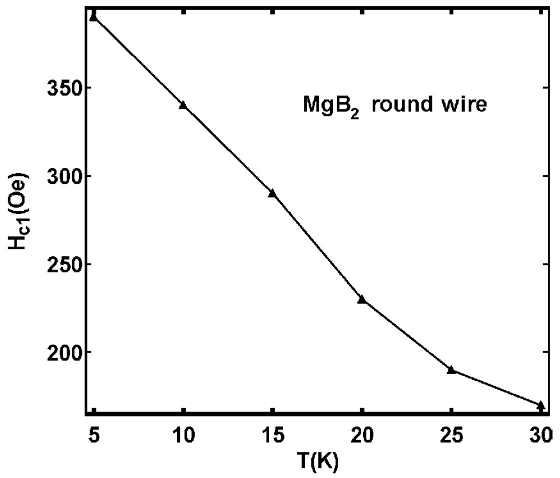

Figure 7. The lower critical field as a function of temperature, showing a linear temperature dependence.

determined by the departure point from the linearity on the slope of the magnetization curve and the results are displayed in figure 7. The criterion of 10% of deviation from linearity was used for the determination of H_{c1}. At 5 K, H_{c1} is around 390 Oe, which is higher than that of MgB_2 bulk samples [17]. Also, the lower critical field shows the linear dependence on temperature, which is similar to that in the YNi_2B_2C system and in high-T_c superconductors. It is believed that this behaviour may be related to the linear dependence of the upper critical field in MgB_2, as reported by some authors [18]. The linear temperature dependence of H_{c1} is considered to be in contrast to an isotropic s-wave superconductivity in MgB_2 [17].

4. Conclusion

In conclusion, we have investigated the phase composition, temperature dependence of J_c, magnetic relaxation behaviour and lower critical field in MgB_2/Ta/Cu wires. The sample has a critical temperature of 38.4 K and a J_c value of 10^5 A cm^{-2} at 5 K in a self-field. In contrast to high-T_c superconductors, J_c is found to decrease linearly with temperature. Magnetic relaxation measurements indicate that the relaxation rate is very small, with a weak temperature dependence, resulting in a high pinning potential. Also, a linear temperature dependence of the lower critical field has been observed in the whole temperature range. Our results provide some useful information for the applications of MgB_2 superconductors.

Acknowledgments

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