

2008

Transport and magnetic critical current in superconducting MgB₂ wires

J. Horvat

University of Wollongong, jhorvat@uow.edu.au

W. K. Yeoh

University of Wollongong, wkyeoh@uow.edu.au

J. H. Kim

University of Wollongong, jhk@uow.edu.au

S. X. Dou

University of Wollongong, shi_dou@uow.edu.au

Publication Details

This article was originally published as Horvat, J, Yeoh, WK, Kim, JH and Dou, SX, Transport and magnetic critical current in superconducting MgB₂ wires, *Superconductor Science and Technology*, 21, 2008, 06S003, 1-6. Original journal article available [here](#)

Transport and magnetic critical current in superconducting MgB₂ wires

J Horvat, W K Yeoh, J H Kim and S X Dou

ISEM, University of Wollongong, NSW 2522, Australia

Received 9 January 2008, in final form 4 February 2008

Published 13 March 2008

Online at stacks.iop.org/SUST/21/065003

Abstract

Direct comparison of the magnetic and transport critical current density (J_c) for the same pieces of copper-sheathed MgB₂ wires shows a large discrepancy in magnitude and field dependence of the two. The value of magnetic J_c can differ from the value of transport J_c by a factor of 10 or more. This discrepancy does not occur merely because of the difference in the voltage at which the magnetic and transport J_c are measured, but mainly because of the specific microstructure of MgB₂. Such microstructure results in superconducting screening on at least two different length-scales, despite the absence of weak links in MgB₂, leading to erroneous magnetic J_c if a simple critical state model is applied to such a system. Consequently, the magnetic J_c cannot be used for analysis of physical processes where the accurate field dependence of J_c needs to be known, such as vortex pinning. The magnetic J_c can still be used for qualitative comparison of MgB₂ samples if they are all of the same size and have the same microstructure, or if their size is large enough so that the magnetic J_c does not depend on the sample size.

1. Introduction

High-quality superconducting MgB₂ wires do not suffer from weak links [1], resulting in a critical current (I_c) of a few hundreds of amps at 20 K and zero field [2–7]. This I_c is difficult to measure directly, using a standard four-probe direct current (DC) method, because of heating of the connecting wires and current contacts on the sample. Consequently, the magnetic measurement of critical current density (J_c) has been a method of choice in a great majority of reports on MgB₂ superconductor. Transport measurements of J_c are usually performed by a DC method with the sample in liquid helium or by a pulsed current method at higher temperatures. Because of the absence of weak links and because the voltage of MgB₂ wires generally increases very sharply with the current at I_c [8], one expects to obtain a good agreement between the transport and magnetic J_c . This has been a generally accepted justification for the use of magnetic J_c in numerous papers reporting not only on improvement of the performance of MgB₂ wires [9–11], but also on studying the underlying physical processes [9, 10, 12, 13].

However, the magnetic J_c has been shown to depend on the size of the sample [14]. The magnetic critical current density (J_{cm}) in zero field is higher for smaller sample size. Conversely, for higher fields, J_{cm} attains higher values for larger samples. Further, if the samples are larger than a few millimetres, there is no size dependence of J_{cm} any more.

This was explained by superconducting screening on at least two different length-scales within the sample [14]: around the whole of the sample and around agglomerates of crystals typically between 10 and 100 μm in size. J_{cm} obtained from the resulting magnetic signal is an artefact of applying a simple critical state model to such a complex screening structure. Additionally, numerical simulations of the field dependence of J_{cm} within the critical state model show that the critical state model gives accurate J_{cm} only for selected cases of sample geometry and pinning strength [15–17]. Nevertheless, J_{cm} continues being widely used for studying MgB₂ due to its convenience, making the need for closer evaluation of the validity of this method more urgent.

This report gives a direct comparison of J_{cm} and transport J_c (J_{ct}) for MgB₂ wires. Limitations of the magnetic method specific to MgB₂ are pointed out and conditions under which J_{cm} can still be useful for providing the true information on sample quality are identified.

2. Experimental details

Critical current density was measured for the same pieces of MgB₂ wires at different temperatures, using magnetic and transport methods. Since J_{ct} is obtained directly from the measurements and obtaining J_{cm} relies on a simplified model, J_{ct} was used as a true J_c of the wires. Obtaining accurate values of J_{ct} was of utmost importance. Because of this, J_{ct}

was measured by a pulsed current method with different rates of the current change. The pulse of the current was obtained either by discharging a capacitor through a coil and sample, or the current was ramped at a constant rate using a Pacific Power 3120AMX AC current source with a UPC32 programmable controller. In the latter case, the maximum current was limited to 200 A. The experimental technique has been described in detail elsewhere [18]. Very fast pulses of current can give misleading results, and only measurements giving identical results for different pulse lengths, both with the capacitor discharge and 3120AMX source, were used in our analysis of Cu-sheathed wires. A further check of the results was provided by direct current (DC) measurements, performed for high fields at which I_c decreased to below 1 A. For DC currents smaller than 1 A, the sample temperature was within 0.1 K of the measured temperature in our set-up, enabling comparison of I_c for pulsed and DC currents. I_c was obtained as the current giving a voltage of $1 \mu\text{V}$ per centimetre of sample length. The value of I_c becomes comparable to the current through the sheath at these fields, and the sheath current was subtracted from the measured I_c as described in [19]. Both DC and pulsed measurements were performed in a modified Quantum Design PPMS system. J_c for all transport measurements was obtained as I_c normalized to the cross-sectional area of the superconducting core. The magnetic field was applied perpendicular to the wire in all transport measurements.

Magnetic measurements were performed with the same piece of sample as the transport ones. The field was swept at a constant rate of 50 Oe s^{-1} . J_{cm} was obtained using the critical state model [20] as

$$J_{cm} = \frac{15\Delta m}{a}, \quad (1)$$

for the field parallel to the sample length. J_{cm} is usually obtained with the field in this direction. Measurements were also performed with the field perpendicular to the sample length, to obtain the screening current path similar to the one in transport measurements, i.e. predominantly along the sample. For this field direction, we used

$$J_{cm} = \frac{15\pi}{4} \frac{\Delta m}{a}. \quad (2)$$

In both equations, Δm is the thickness of the magnetic hysteresis loop and a is the radius of the sample. All measurements were performed at 10, 20 and 25 K.

To avoid effects of the magnetic sheath on the measured J_{ct} , copper was used as a sheath material of MgB_2 wire. Magnetic measurements also benefited from a non-magnetic sheath, because there was no need to remove the sheath from the wire, thus avoiding the risk of damaging the superconducting core. The samples were prepared by the powder-in-tube, *in situ* method [21]. Copper tubes were filled with appropriate amounts of Mg and B powder, sealed, drawn, wrapped in Ta foil and heated at 630°C for 20 min in flowing Ar. The final diameters of the wire and superconducting core were 1.5 and 1.0 mm, respectively. A critical temperature of 37.9 K was obtained as the onset of superconducting screening in the temperature dependence of AC susceptibility.

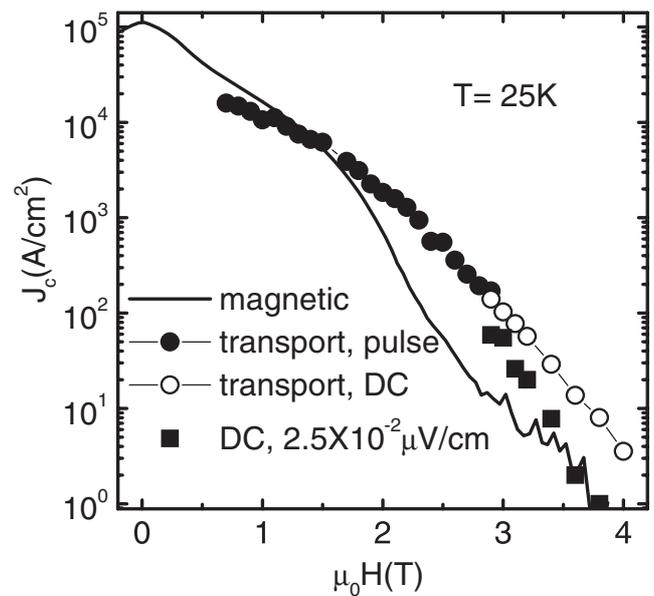


Figure 1. Comparison of magnetic (solid line) and transport (round symbols) J_c for the same piece of Cu-sheathed MgB_2 wire at 25 K, with log-linear scales. Solid and open round symbols are for the pulsed and DC current source, respectively. Square symbols are the extrapolation of transport J_c measured by the DC method to the voltage criterion used in the magnetic measurements of J_c . The magnetic measurements were performed with the field parallel to the wire axis, with a wire length of 5 mm.

Cu-sheathed samples have lower J_c than the current best samples, sheathed with Fe. For this reason, measurements were also performed on high-quality Fe-sheathed samples doped with nano-SiC and malic acid, for comparison. The iron sheath was removed from samples for magnetic measurements.

3. Results and discussion

The field dependence of J_{cm} and J_{ct} for the same MgB_2/Cu wire at 25 K is shown in figure 1. The field was parallel to the sample length in magnetic measurements. The pulsed and DC J_{ct} are in good agreement with each other (round symbols). This is not surprising because the experimental noise in the pulsed measurements was a couple of $\mu\text{V cm}^{-1}$, and the $V-I$ characteristics were relatively steep. On the other hand, there is apparent discrepancy between J_{cm} and J_{ct} , both in their values and in their field dependence, $J_c(H)$. $J_{cm}(H)$ exhibits two steps at about 0.5 and 2 T (solid line), which reflects the dominance of superconducting screening on different length-scales in different field ranges [14, 22]. For some fields, J_{cm} and J_{ct} differ by one order of magnitude. J_{cm} and J_{ct} overlap at about 1.3 T in figure 1; however, the overlap field depends on the temperature and is different for different samples. Because $J_{cm}(H)$ depends on the sample size [14, 22], the overlap field also depends on the sample size.

To further appreciate the difference between J_{cm} and J_{ct} , the same results are shown in figure 2(a) for another Cu-sheathed sample at 20 K, with linear scales. The field was perpendicular to the wire axis in the magnetic measurements. Because transport J_c is the real useful J_c that flows

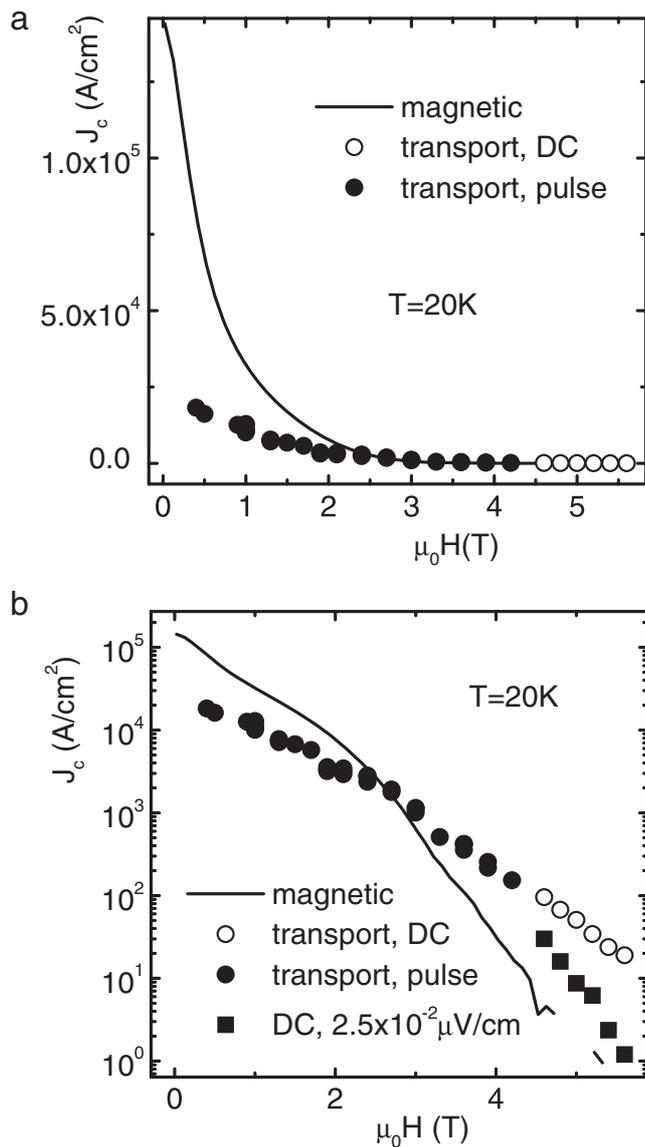


Figure 2. (a) Comparison of magnetic (solid line) and transport (round symbols) J_c for the same piece of Cu-sheathed MgB_2 wire at 20 K, with both scales linear. The discrepancy between the values of J_c obtained by the two methods at low fields is obvious. Magnetic measurements were performed with the field perpendicular to the wire axis, with a wire length of 4.3 mm. (b) The same as in (a), but with log-linear scales. Square symbols are the extrapolation of transport J_c measured by the DC method to the voltage criterion used in the magnetic measurements of J_c .

through the whole of the sample, magnetic measurements substantially overestimate the real J_c at low fields, whereas they underestimate it at high fields. Qualitatively the same results were obtained at all measured temperatures for a variety of samples with both parallel and perpendicular field in magnetic measurements. Figure 2(b) shows the same measurements with log-linear scales. There is qualitatively the same difference between J_{cm} and J_{ct} as for magnetic measurements with parallel field (figure 1). This result is not surprising, because the current does not flow straight through MgB_2 wires. Instead, it meanders between cavities, in both the perpendicular and parallel directions. As a consequence,

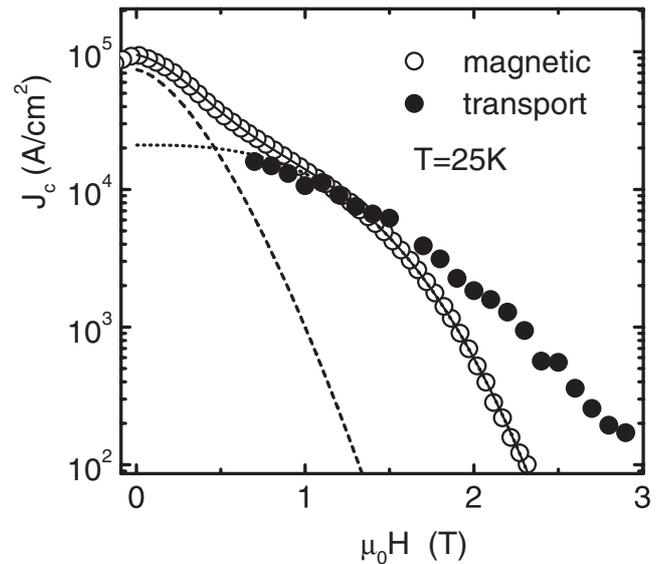


Figure 3. Field dependence of magnetic and transport J_c , with fit using equation (3). The first and second terms in equation (3) are shown by dashed and dotted lines, respectively. The solid line is the sum of the two, giving an excellent fit to the magnetic J_c (open symbols). The dotted line overlaps with the magnetic J_c for $\mu_0 H > 1.3$ T. The transport J_c (open symbols) overlaps with the second term in equation (3) (dotted line) only for $\mu_0 H \approx 1.3$ T, after which the dotted line overlaps with the magnetic J_c because the first term in equation (3) is negligible for high fields. The transport J_c agrees with the second term in equation (3) (dotted line) better than with the whole of equation (3) (solid line). The wire length in magnetic measurements was 5 mm and the field was parallel to the wire axis.

$J_{ct}(H)$ for Fe-sheathed wires can overlap for parallel and perpendicular fields at high fields and temperatures, for which the effect of the Fe sheath on $J_{ct}(H)$ is negligible [18, 23].

The difference between J_{cm} and J_{ct} can be affected by the difference in the voltage criteria used for the definition of J_c in transport and magnetic measurements. This difference can be especially significant at high fields, where the voltage changes more gradually with current at $J = J_c$. To check this effect, DC measurements of J_{ct} were performed at 1, 5 and 10 $\mu\text{V cm}^{-1}$ and extrapolated to the voltage criterion used in the magnetic measurements: $2.5 \times 10^{-2} \mu\text{V cm}^{-1}$. A power-law relationship between J_c and the voltage criterion was used in this extrapolation, as obtained from classical flux creep theory [24, 25], with logarithmic dependence of the activation energy U on J [26]. The extrapolated values of J_{ct} are shown by solid square symbols in figures 1 and 2(b). While the thus obtained J_{ct} extrapolated to lower fields seems to be in good agreement with pulsed current measurements at lower fields (round solid symbols), it has different values and field dependence than J_{cm} . This again confirms the inadequacy of J_{cm} when describing the details in $J_c(H)$.

The discrepancy between J_{cm} and J_{ct} in MgB_2 occurs predominantly because of the characteristic microstructure of the superconducting MgB_2 core. Despite the absence of weak links in good MgB_2 wires, there are superconducting screening currents flowing on different length-scales due to sample porosity and agglomeration of superconducting

crystals [14, 22]. The relative contribution of each of the screening currents to the measured magnetic moment can be obtained thanks to the different field dependence of each of the screening currents. This is shown in figure 3 for the same sample as in figure 1, with the exact procedure given in [22]. J_{cm} in figure 3 contributed to by superconducting currents flowing on two different screening lengths can be fitted by two stretched exponential functions:

$$J_{cm} = 7.4 \times 10^4 \text{ A cm}^{-2} \exp\left(-\left(\frac{H}{0.37 \text{ T}}\right)^{1.55}\right) + 2.1 \times 10^4 \text{ A cm}^{-2} \exp\left(-\left(\frac{H}{1.29 \text{ T}}\right)^{2.9}\right). \quad (3)$$

The stretched exponential function was chosen because the experimental points linearize when plotted in a $-\text{d}(\ln(J_{cm}))/\text{d}H$ versus H plot with log–log scales [22] and it is also obtained in classical vortex creep model [24, 25]. The first and second terms in equation (3) are shown in figure 3 by dashed and dotted lines, respectively. The solid line is the sum of the two terms, giving an excellent fit to experimental data for J_{cm} (open symbols in figure 3). The contribution of the first term in equation (3) is negligible for $\mu_0 H > 1.3$ T, and the second term in equation (3) alone gives an excellent fit to the experimental points for these fields. The contribution of the first term in equation (3) starts decreasing with the sample size, as it becomes smaller than a few millimetres [22]. When the sample size is comparable to the size of the crystal agglomerates in the sample, the first term is not observed any more [22]. This is the main reason for obtaining erroneous J_{cm} using the critical state model (i.e. equations (1) and (2)). The different screening length for each of the two contributions in equation (3) should be taken into account when calculating J_{cm} in the critical state model, separately for the contribution of each of the screening currents to the measured magnetic moment. In reality, equation (3) is a fit to $\Delta m(H)$, not to $J_c(H)$.

Figure 3 shows that J_{ct} (solid symbols) agrees better with the second term in equation (3) (dotted line) than with the overall measured J_{cm} (open symbols). This is because the second term in equation (3) represents superconducting screening around the whole of the sample and the correct value for a was used in equations (1) and (2) when calculating J_{cm} . The first term in equation (3) represents screening around agglomerates of crystals and has little to do with J_{ct} that passes through the whole of the sample.

Nevertheless, this agreement between J_{ct} and the second term in equation (3) is not perfect. Numerous reports show that the critical state model can give accurate $J_c(H)$ only for thin samples in a perpendicular field or for weak field dependence of J_c [15–17]. Further, numerical simulations show that major defects in the superconducting core will affect J_{cm} and J_{ct} differently [27]. Finally, the field dependence of both of the terms in equation (3) was shown to depend on the sample size [22]. This size dependence indicates that there is a correlation between the two screening currents in equation (3), since both of them have to pass through agglomerates of crystals. This should result in a complex distribution of the screening currents within the agglomerates, so that the net *local*

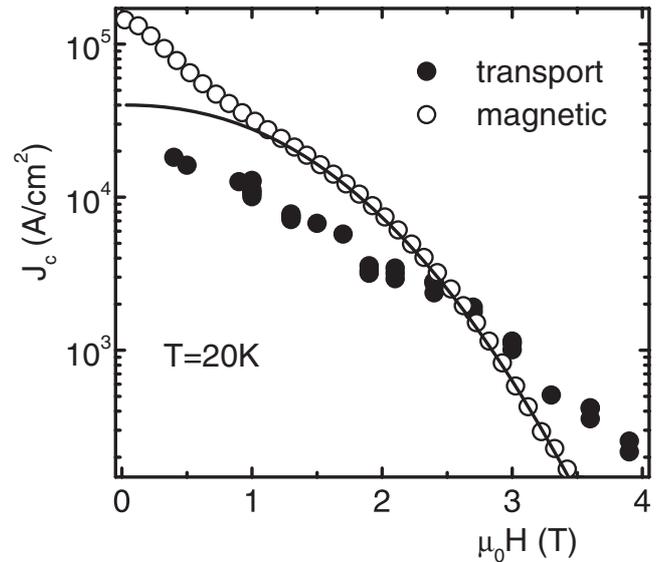


Figure 4. Field dependence of magnetic (open symbols) and transport (solid symbols) J_c for a Cu-sheathed MgB_2 wire at 20 K. The solid line represents the second term in equation (3). The field was perpendicular to the wire axis in magnetic measurements.

current density in them keeps the value of J_c . All these reasons are likely to be responsible for the difference between J_{ct} and the second term in equation (3).

There is no general rule regarding the exact differences between J_{ct} and the second term of equation (3). For some samples, J_{ct} seems to be larger than the second term in equation (2) at low fields (figure 3), whereas it is lower for other samples (figure 4). This also changes with the temperature and sample size. However, J_{ct} is always higher than J_{cm} and the second term in equation (3) for high fields.

Therefore, J_{cm} and J_{ct} have the same value only for one field (figures 1–3) and J_{cm} is sample size dependent. Consequently, $J_{cm}(H)$ cannot be used as a true property of an MgB_2 wire and no conclusions can be made on the underlying physical processes if the exact form of $J_c(H)$ is required. For example, an analysis of the field dependence of the pinning force density obtained as $F_p = H J_{cm}(H)$ to obtain the type of vortex pinning in differently doped MgB_2 wires [28] is inherently erroneous for this reason. There is only a small difference in the fitting functions for $F_p(H)$ that help distinguish between different pinning mechanisms [28], requiring very accurate $J_c(H)$. $J_{cm}(H)$ is far from an accurate presentation of the real $J_c(H)$ (figures 1–3), often resulting in non-physical forms for the thus obtained $F_p(H)$, inconsistent and inconclusive results. This raises the question if $J_{cm}(H)$ can be used at all to characterize the quality of MgB_2 wires and if so, what are the limits of its use.

There are numerous reports showing the same *trend* in the change of $J_{cm}(H)$ and $J_{ct}(H)$ for differently prepared MgB_2 [11, 29, 30], even though J_{cm} and J_{ct} are often measured for different pieces of sample and with the iron sheath having to be removed to enable magnetic measurements in low fields. However, the exact values and field dependences of J_{cm} and J_{ct} are different. Our results (figures 1–3) show that this difference does not occur only because different pieces of sample were

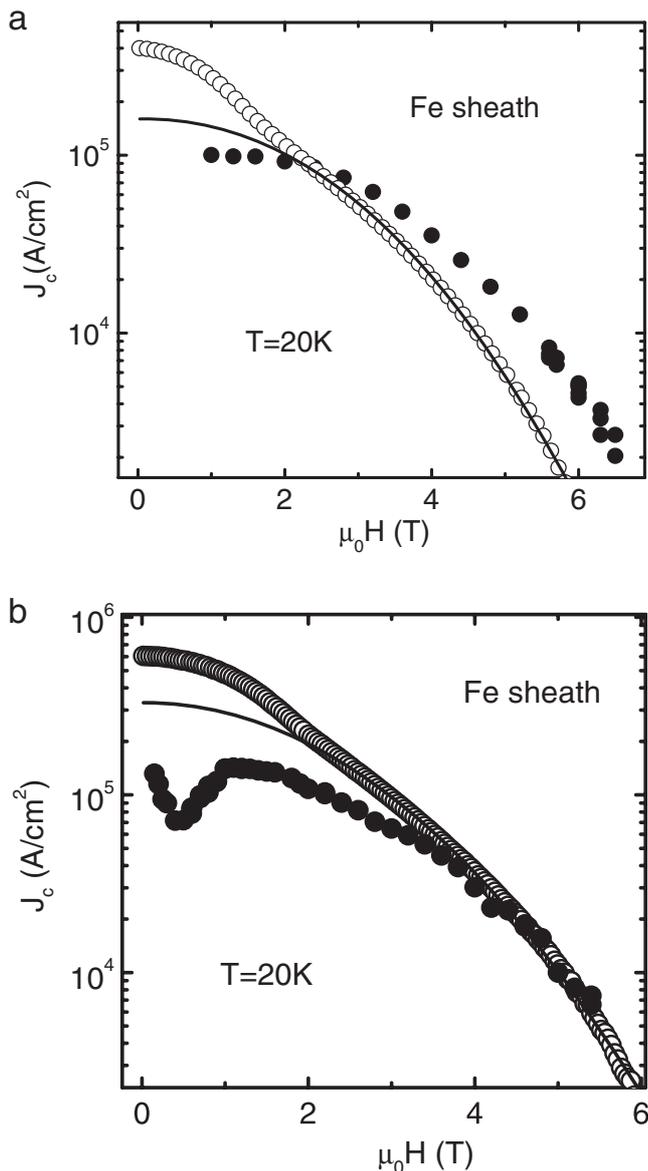


Figure 5. (a) Field dependence of magnetic (open symbols) and transport (solid symbols) J_c for a high-quality Fe-sheathed, malic acid doped MgB₂ wire at 20 K. The sample length for J_{cm} was 2.5 mm. The solid line represents the second term in equation (3). (b) Field dependence of magnetic (open symbols) and transport (solid symbols) J_c for a high-quality Fe-sheathed, nano-SiC doped MgB₂ wire at 20 K. The solid line represents the second term in equation (3). The peak in transport $J_c(H)$ is obvious for the SiC doped sample, while it is not seen for malic acid doped sample because I_c was too high to be measured for fields where the peak occurs for this sample at 20 K. The field was parallel to the sample axis in the magnetic measurements, with the iron sheath removed.

used for transport and magnetic measurements or because of the effects of removing the iron sheath. All this implies that J_{cm} can be used for qualitative comparisons of the *change* of J_c for MgB₂ wires subjected to different preparation procedures, such as doping. However, caution has to be exercised because of the sample size dependence of J_{cm} . Our earlier research shows that the value of J_{cm} decreases with sample size by up to 80% for low fields [14]. Conversely, J_{cm} increases with sample

size by up to one order of magnitude for high fields [14]. The exact magnitude of the sample size effect depends on the typical length-scales of the agglomerates of crystals in the samples [22]. For samples much larger than the size of agglomerates (typically larger than about 5 mm), J_{cm} does not depend on the sample size [14]. However as the sample size decreases, J_{cm} starts changing. The characteristic size of the sample for which this effect becomes significant depends on the microstructure of the sample. This artificial variation in J_{cm} with the sample size can become larger than the change of real J_c due to differences in the preparation procedures. Therefore, a reliable *trend* in $J_{cm}(H)$ for samples made with different preparation procedures can only be obtained in two cases: all the samples either have to be large enough not to be affected by the artefact of the size effect, or all the samples have to be of the same size and have the same microstructure.

The results presented so far are for Cu-sheathed samples, which do not display the effects of a ferromagnetic sheath on J_c , but which have lower J_c than the best current MgB₂ wires. These high- J_c samples could in principle have a qualitatively different form of $J_{cm}(H)$ than the Cu-sheathed samples due to better connectivity. If the microstructure is substantially improved, the effect of different superconducting screening lengths on the measured J_{cm} need not be as strong as for Cu-sheathed samples, and the agreement between J_{cm} and J_{ct} could be better. For this reason, we also show $J_{ct}(H)$ and $J_{cm}(H)$ for two high-quality Fe-sheathed samples.

Figures 5(a) and (b) respectively show $J_{ct}(H)$ and $J_{cm}(H)$ for malic acid doped [31] and nano-SiC doped MgB₂ samples sheathed with Fe. The Fe sheath affects the form of $J_{ct}(H)$ in low field, resulting in a dip and a peak (figure 5(b)) [18, 23]. The peak is not visible in figure 5(a) because J_{ct} could not be measured at lower fields, where the dip occurs. Despite the presence of the Fe sheath, the difference in $J_{cm}(H)$ and $J_{ct}(H)$ is qualitatively the same as for Cu-sheathed samples. Therefore, even the best quality samples available today will produce erroneous details in $J_{cm}(H)$. However, the trend of change of $J_{cm}(H)$ with various preparation procedures will still be correct if precautions are taken to keep the artefacts of complex superconducting screening the same for all the samples that are compared.

4. Conclusions

The magnetic J_c does not represent an accurate J_c of MgB₂ wires, both in terms of absolute value and field dependence of J_c . The values of J_{cm} are closer to J_{ct} if only the second term in equation (3) is used, applying the procedure described earlier [22]. Particularly erroneous conclusions can be drawn when using J_{cm} to obtain the type of vortex pinning in the sample by analysing the field dependence of the pinning force density, $F_p = J_c H$. This is because the exact field dependence of F_p is absolutely critical in determining the type of vortex pinning, and the field dependence of J_{cm} is an artefact of the experimental method. However, J_{cm} can still be useful for relative comparisons of different MgB₂ samples, providing they are either large enough so that their J_{cm} does not depend on sample size, or their microstructure and size are the same. In such a way, the effect of different screening lengths on the

J_{cm} of studied samples is the same for all of them and the relative quality of the samples can be assessed, even though the value and field dependence of J_{cm} are erroneous. This is supported in practice, where a relative improvement in $J_{cm}(H)$ is often accompanied by a relative improvement in $J_{ct}(H)$ for different samples. It should be stressed that the value and field dependence of J_{cm} are still erroneous even for large samples. $J_{cm}(H)$ still exhibits the steps at characteristic fields that are absent in J_{ct} and the value of J_{cm} is different from J_{ct} for samples of all sizes that can be measured in a typical magnetometer. Unusual or inconsistent conclusions obtained on the basis of the analysis of $J_{cm}(H)$ are most likely a consequence of these artefacts in $J_{cm}(H)$.

Acknowledgment

This work was supported by the Australian Research Council.

References

- [1] Larbalestier D C et al 2001 *Nature* **410** 186
- [2] Jin S, Mavoori H and van Dover R B 2001 *Nature* **411** 563
- [3] Kovač P, Hušek I, Melišek T, Martínez E and Dhalle M 2006 *Supercond. Sci. Technol.* **19** 1076
- [4] Togano K, Nakane T, Fujii H, Takeya H and Kumakura H 2006 *Supercond. Sci. Technol.* **19** L17
- [5] Fang H, Putman P T, Padmanabhan S, Zhou Y X and Salama K 2004 *Supercond. Sci. Technol.* **17** 717
- [6] Flükiger R, Lezza O, Beneduce C, Musolino N and Suo H L 2003 *Supercond. Sci. Technol.* **16** 264
- [7] Sumption M D, Susner M A, Bhatia M, Rindfleisch M A, Tomsic M J, McFadden K J and Collings E W 2007 *IEEE Trans. Appl. Supercond.* **17** 2838
- [8] Horvat J, Yeoh W K and Miller L M 2005 *Appl. Phys. Lett.* **87** 102503
- [9] Martinelli A, Tarantini C, Lehmann E, Manfrinetti P, Palenzona A, Pallecchi E, Putty M and Ferdeghini C 2008 *Supercond. Sci. Technol.* **21** 012001
- [10] Fujii H, Togano K and Ozawa K 2008 *Supercond. Sci. Technol.* **21** 015002
- [11] Dou S X, Soltanian S, Horvat J, Wang X L, Zhou S H, Ionescu M, Liu H K, Munroe P and Tomsic M 2002 *Appl. Phys. Lett.* **81** 3419
- [12] Martínez E, Mikheenko P, Martínez-López M, Millán A, Bevan A and Abell J S 2007 *Phys. Rev. B* **75** 134515
- [13] Gao Z, Ma Y, Zhang X, Wang D, Yu Z, Watanabe K, Yang H and Wen H 2007 *Supercond. Sci. Technol.* **20** 485
- [14] Horvat J, Soltanian S, Wang X L and Dou S X 2004 *Appl. Phys. Lett.* **84** 3109
- [15] Chen D-X and Goldfarb R B 1989 *J. Appl. Phys.* **66** 2489
- [16] Sanchez A and Navau C 2001 *Supercond. Sci. Technol.* **14** 444
- [17] Johansen T H and Bratsberg H 1995 *J. Appl. Phys.* **77** 3945
- [18] Horvat J, Soltanian S, Wang X L and Dou S X 2003 *IEEE Trans. Appl. Supercond.* **13** 3324
- [19] Babić E, Kušević I, Dou S X, Liu H K and Hu Q Y 1994 *Phys. Rev. B* **49** 15312
- [20] Bean C P 1964 *Rev. Mod. Phys.* **36** 31
- [21] Wang X L, Soltanian S, Horvat J, Liu A H, Qin M J, Liu H K and Dou S X 2001 *Physica C* **361** 149
- [22] Horvat J, Soltanian S, Pan A V and Wang X L 2004 *J. Appl. Phys.* **96** 4342
- [23] Horvat J, Wang X L, Soltanian S and Dou S X 2002 *Appl. Phys. Lett.* **80** 829
- [24] Anderson P W 1962 *Phys. Rev. Lett.* **9** 309
- [25] Beasley M R, Labush R and Webb W W 1969 *Phys. Rev.* **181** 682
- [26] Keshavarzi S, Qin M J, Soltanian S, Liu H K and Dou S X 2004 *Physica C* **408** 601
- [27] Bartolome E, Gömöry F, Granados X, Puig T and Obradors X 2005 *Supercond. Sci. Technol.* **18** 388
- [28] Dew-Hughes D 1974 *Phil. Mag.* **30** 293
- [29] Fujii H, Togano K, Kumakura H and Ozawa K 2007 *Supercond. Sci. Technol.* **20** 579
- [30] Ma Y, Kumakura H, Matsumoto A and Togano K 2003 *Appl. Phys. Lett.* **83** 1181
- [31] Kim J H, Zhou S, Hosain M S A, Pan A V and Dou S X 2006 *Appl. Phys. Lett.* **89** 142505