Characterisation of a MgB$_2$ wire using different current pulse shapes in a pulsed magnetic field

Abstract. A pulse field-pulse current system for critical current measurements has been modified to allow control of the current pulse shape. Regression analysis of the voltage vs. current behaviour has been used to determine the critical current and $I_c(0)$ value using a specified electric field criterion from a single measurement cycle, in place of the previous qualitative approach from a series of pulses. The results for a superconducting magnesium diboride wire agree well with conventional DC measurements in a constant magnetic field.

Streszczenie. System do pomiarów prądu krytycznego przy użyciu impulsowego prądu i pola magnetycznego został zmodernizowany, umożliwiając kontrolę kształtu impulsu prądu. Prąd krytyczny i $I_c(0)$ można obliczyć na podstawie regresji i kryterium pola elektrycznego z pojedynczego cyklu pomiarowego w zastępstwie poprzednio używanego jakościowego sposobu opartego na serii impulsów. Wyniki otrzymane dla przewodów z dwuborkiem magnezu dobrze zgadzają się z konwencjonalnymi pomiarami prądem i polem magnetycznym.

Keywords: pulse measurements, magnesium diboride, critical current, Regression analysis of the voltage vs. current behaviour has been used to determine the critical current and $I_c(0)$ value using a specified electric field criterion from a single measurement cycle, in place of the previous qualitative approach from a series of pulses. The results for a superconducting magnesium diboride wire agree well with conventional DC measurements in a constant magnetic field.

Introduction

The pulse field-pulse current (PFPC) technique is a promising method for the transport critical current $I_c(B)$ characterisation of short superconductor samples, allowing high fields and high currents to be achieved economically and without excessive sample heating. However, for some samples discrepancies in measured $I_c(B)$ between this and the standard constant field direct current (CFDC) technique arise. The PFPC method often slightly overestimates the CFDC results in higher magnetic fields, as reported recently for an MgB$_2$/Cu wire [1]. Larger discrepancies, typically an underestimate of $I_c$ at low fields, can occur in some conductor architectures (e.g. those with a large number of filaments) due to flux jumps arising from the non-uniform current distribution resulting from the transient magnetic self-field [2]. A model for the intrinsic stability of a multifilamentary Nb-Ti/Cu-Mn/Cu wire was recently shown to describe quite well the PFPC measurement [3]. The PFPC technique may also underestimate $I_c(B)$ due to difficulties in current transfer from the current leads to the superconducting region through the resistive matrix of short samples, as has been shown by finite element analysis [4].

In all reported measurements [1-4] the critical current $I_c(B)$ was determined by comparing qualitatively the shape of the voltage vs. time response of the sample from a series of approximately sinusoidal current pulses of increasing amplitude, each delivered during a plateau of magnetic field. The qualitative nature of this analysis and the relatively high noise level for high sampling rate data acquisition meant that a low and strictly defined electric field criterion could not be applied. The near-sinusoidal current pulse shape also meant that the rate of change of current, and hence the induced voltage, was time dependent, further complicating analysis. For the measurements reported here, the capacitive discharge current source used previously has been replaced by one capable of delivering accurately any arbitrary shape and length current pulse (Fig.1). In this contribution, regression analysis is applied to the voltage vs. current response to allow the critical current to be determined using a $1 \text{ µV cm}^{-1}$ criterion for sinusoidal and linear current pulse shapes, and the differences between them and CFDC measurements are discussed.

Experimental methods

A 0.58 mm diameter wire with the MgB$_2$ core occupying 47 % of its cross-sectional area was manufactured using the powder-in-tube (PIT) method with an oxide dispersion strengthened copper (Glidcop™) sheath (Fig.1). The starting core composition was Mg+2B+0.09Cu, i.e. with copper powder additions to minimise the diffusion of copper from the Glidcop sheath and thus maximising the fraction of MgB$_2$ in the core [5,6]. A 7 cm long wire sample was heat treated with a 20 °C min$^{-1}$ heating rate at 700 °C for 5 min in a flowing 95 % Ar + 5 % H protective atmosphere (Fig.1).

Sample 18 mm in length were measured perpendicular to the magnetic field and in liquid helium by the CFDC technique in a Bitter magnet (type Bitter 100, BM1 [7]) in the ILHMFLT (Wroclaw, Poland), with a voltage tap spacing of 6 mm and a current ramp rate up to 2 A s$^{-1}$ (Fig.2 a)).

Fig. 1 Temperature profiles of the heat treatments of the wire. Insert shows an optical microscope micrograph of the wire cross-section.

Fig. 2 Schematic diagrams showing the mounting of wire samples for: a) constant field direct current (CFDC) and b) pulse field pulse current (PFPC) measurements. In fig. b), the coil below the sample is used to measure the voltage induced by the pulsed magnetic field, so that this contribution to the sample voltage can be cancelled. Temperature sensors and magnetic field coils are not shown to scale.
An 11 mm long sample was measured by the PFPC technique by placing it perpendicular to the magnetic field and in liquid helium (Fig.2 b). The voltage from taps separated by 2.6 mm was amplified (10× gain), summed with a voltage proportional to the cancellation coil (Fig.2 b) signal to correct for the induced voltage, and recorded by a high sampling rate ADC system (Fig.3).

A signal generator was used to control the current delivered by a current source consisting of 5 power supplies (4 × KEPCO 20-20M + 1 × KEPCO 36-12M) in parallel (Fig.3). A current of 92 A (4 × 20 A + 12 A) with a minimum rise or fall time of 35 μs (10%-90% $I_{\text{max}}$) could be achieved. 4 ms long current pulses with sinusoidal and linear shapes were delivered during the plateau of the magnetic field pulse (Fig.4).

**Signal processing**

Two types of voltage signals were recorded from the voltage taps of the sample before proceeding to the actual $I_c(B)$ measurements. Firstly, the voltage responses to a series of current pulses with increasing amplitude without an applied magnetic field were recorded as reference signals corresponding to the voltage induced by the change of the sample current with time (an example is shown in Fig.5). Secondly, the voltage responses to a series of magnetic field pulses with increasing amplitude without passing a sample current were recorded as reference signals corresponding to the voltage induced by the change of the magnetic field with time. Most of this voltage had already been removed by correcting with the signal provided by the cancellation coil, but a small signal remained. These voltage components were subtracted from the voltage signal recorded from the sample during simultaneous pulses of magnetic field and current for $I_c$ determination: for example, the sample voltage due to a current pulse with an amplitude of 92 A during a magnetic field pulse with a 1 T plateau was corrected by the subtraction of the separate voltage responses to (i) a 92 A current pulse without magnetic field and (ii) a magnetic field pulse with a 1 T plateau without sample current (Fig.5).

Results and discussion

The MgB$_2$/Glidcop wire prepared for this comparison of measurement techniques achieved a critical current density, $J_c$, of $10^4$ A cm$^{-2}$ at 3 T and 4.2 K, which is about three times lower than for recently reported wires in a copper sheath and with copper powder additions [5,6]. However, this and the small wire diameter (0.58 mm) helped to achieve a relatively low value of $I_c$, which was very desirable because it allowed measurements to be performed in low magnetic fields with the available current supplies. The use of a low resistivity metal sheath (Glidcop) and its thin wall also helped to minimise current transfer voltages during measurements on such short wire samples with closely-spaced current contacts and voltage taps. Any contribution of a very thin MgCu$_2$ reaction layer (Fig.1) to the current transfer is also believed to be small as in CFDC measurements no resistive slope in the sample voltage due to current transfer was observed.

With the aim of better differentiating between the resulting $E$-$I$ curves from linear and sinusoidal current ramps in Fig.6, the amplitude of current pulses for each magnetic field pulse was selected in such a way that the maximum electric field (after corrections) from the sample at maximum current was close to 200 μV cm$^{-1}$. This ensured that the knee of the $E$-$I$ curve for the sinusoidal ramp was measured when the rate of change of sample current was decreasing to zero.

Critical currents obtained by regression analysis of the voltage vs. current behaviour from both CFDC and PFPC techniques are in good agreement (Fig.6 and Fig.7). Linear and sinusoidal pulse shapes resulted in very similar voltage vs. current behaviour from both CFDC and PFPC measurement techniques achieved a critical current density, $J_c$, of $10^4$ A cm$^{-2}$ at 3 T and 4.2 K, which is about three times lower than for recently reported wires in a copper sheath and with copper powder additions [5,6]. However, this and the small wire diameter (0.58 mm) helped to achieve a relatively low value of $I_c$, which was very desirable because it allowed measurements to be performed in low magnetic fields with the available current supplies. The use of a low resistivity metal sheath (Glidcop) and its thin wall also helped to minimise current transfer voltages during measurements on such short wire samples with closely-spaced current contacts and voltage taps. Any contribution of a very thin MgCu$_2$ reaction layer (Fig.1) to the current transfer is also believed to be small as in CFDC measurements no resistive slope in the sample voltage due to current transfer was observed.

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Critical currents obtained by regression analysis of the voltage vs. current behaviour from both CFDC and PFPC techniques are in good agreement (Fig.6 and Fig.7). Linear and sinusoidal pulse shapes resulted in very similar estimates of $I_c$, without any systematic trend in these values. The noise level for voltage measurements without software averaging was on the level of 20 μV, so it is likely that the previously-reported qualitative approach [1-4] would correspond to an electric field criterion at least one order of magnitude higher. Adopting the same criterion may therefore account for ~10% $I_c(0)$ of the discrepancy between the previously-reported PFPC and CFDC techniques. Clearly, when using the same criterion, some $I_c$...
Ic shape and duration. This is essential for optimising PFPC very high degree of flexibility in controlling the current pulse shape, and most of the differences being caused by the CFDC results, with little dependence on the current pulse range of currents which can be achieved but provides a linear current pulse shapes. 

Measurements, but quite similar for both sinusoidal and measured in PFPC are lower than those from CFDC much higher ramp rate for the PFPC technique. 

The current source used in the present work restricts the range of currents which can be achieved but provides a very high degree of flexibility in controlling the current pulse shape and duration. This is essential for optimising PFPC l(I) characterisation, particularly in the high field region where the previously explained heating and stability effects are less significant [2-4]. A systematic study of the effect of ramp rate, as controlled by pulse duration, is under way.

discrepancy remains. Most of these discrepancies arise from the fact that the E-l curves from PFPC are shifted to higher currents due to the high current ramp rate as was reported in [8], but with much lower n values. The n values measured in PFPC are lower than those from CFDC measurements, but quite similar for both sinusoidal and linear current pulse shapes.

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Conclusions
A refinement of the PFPC technique for l(I) measurement has been demonstrated, in which l, can be determined at a chosen electric field criterion from a single current pulse, I, and n values are in good agreement with CFDC results, with little dependence on the current pulse shape, and most of the differences being caused by the much higher ramp rate for the PFPC technique.

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Fig.6 Electric field vs. current recorded from the wire during constant field direct current (CFDC) and pulse field pulse current (PFPC) measurements with two shapes of current ramp (Fig. 2). The inset table presents the critical current l, and n values obtained for each curve.

Fig.7. Critical current (density), Ic(B), vs. magnetic field from PFPC measurements for MgB2 wire (Fig.1) at 4.2 K.

Field [T] | l [A] | n value | DC | PFPC
---|---|---|---|---
1 | 50.7 | 62.6 | 57.3 | 28.5 | 19.8 | 19.4 | DC | PFPC
2 | 24.4 | 23.6 | 22.1 | 17.9 | 11.9 | 10.8 | 3 | 12.1 | 11.7 | 11.6 | 17.6 | 9.1 | 0.6
4 | 5.4 | 5.5 | 6.7 | 16.6 | 7.4 | 8.6 | 5 | 1.6 | 1.8 | 1.7 | 6.1 | 4.6 | 4.3

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