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Influence of Twisting and Bending on the J_c and n -value of Multifilamentary MgB_2 Strands

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Abstract

The influences of strand twisting and bending (applied at room temperature) on the critical current densities, J_c , and n -values of MgB_2 multifilamentary strands were evaluated at 4.2 K as function of applied field strength, B . Three types of MgB_2 strand were evaluated: (i) advanced internal magnesium infiltration (AIMI)-processed strands with 18 filaments (AIMI-18), (ii) powder-in-tube (PIT) strands processed using a continuous tube forming and filling (CTFF) technique with 36 filaments (PIT-36) and (iii) CTFF processed PIT strands with 54 filaments (PIT-54). Transport measurements of $J_c(B)$ and n -value at 4.2 K in fields of up to 10 T were made on: (i) PIT-54 after it was twisted (at room temperature) to twist pitch values, L_p , of 10–100 mm. Transport measurements of $J_c(B)$ and n -value were performed at 4.2 K; (ii) PIT-36 and AIMI-18 after applying bending strains up to 0.6% at room temperature.

PIT-54 twisted to pitches of 100 mm down to 10 mm exhibited no degradation in $J_c(B)$ and only small changes in n -value. Both the $J_c(B)$ and n -value of PIT-36 were seen to be tolerant to bending strain of up to 0.4%. On the other hand, AIMI-18 showed $\pm 10\%$ changes in $J_c(B)$ and significant scatter in n -value over the bending strain range of 0–0.6%.

1 Introduction

With a transition temperature T_c of 39 K, MgB_2 offers the possibility of helium-free operation [1]. This, together with the fact that MgB_2 is available as a round, multifilamentary, twisted strand presents it as a promising superconductor for 20 K application. Several different methods have been developed to fabricate MgB_2 strands: (i) the *in situ*, powder-in-tube (PIT) process [2], (ii) the *ex situ* PIT process [3]; (iii) the *in situ* reactive magnesium infiltration process [4] and its recent variants. Recent years have seen significant developments of MgB_2 strands [5–12]. The best transport properties so far have been seen in “advanced internal Mg infiltration” method (AIMI) strands with their 10 T, 4.2 K J_c s of over 10^4 A/cm² [13]. Much developmental effort has focused on improving the critical current density, J_c , with less attention to n -values especially in the 10–30 K range, even though a high n -value is important for practical applications. Given the potential of

MgB₂ for liquid helium free applications, the values of J_c and n -value in the 5–30 K range is of substantial interest. Accordingly we report here on the J_c s and n -values of an 18-filament AIMI strand at fields of up to 12 T and at temperatures of from 4.2 K–30 K.

In addition to the high J_c and n -value requirements practical superconducting strands need to be both multifilamentary and twisted in the interests of flux jump stability and AC-loss reduction. The twisting process generates strain accompanied by the possibility of reduced J_c [14–18] and n -value. However, recent developments at HyperTech Research Inc (HTR) have led to strands with high filament counts and a satisfactory tolerance to pre-reaction twisting. Here we present a study of the twist-pitch dependence of J_c and n -value of a HTR processed PIT conductor.

In addition to satisfactory current transport and twist properties, the ability of a strand, and indeed a conductor assembled from it, to withstand bending strain is of interest for applications. It is of course possible to construct magnets using a wind-and-react technique, in which case bending strain is not a consideration, but insulation and the heat treatment of the coil former become issues. Magnets can also be constructed using a react-and-wind approach, which allows more flexibility in insulation, but requires that the strands be tolerant to post reaction bending during magnet winding. This type of strain is distinct from that experienced by the strand during magnet excitation in which case well-defined tensile, compressive, or transverse pressure induced strains will be applied at the operating temperature (4–30 K for MgB₂). Such effects, resulting for example from thermal cycling stresses and Lorentz forces generated in MgB₂ strands during magnet operation have been investigated [19–23]. In this study we focus on the effect of bending strain applied to reacted strands at room temperature, the relevant parameter for developing magnet winding procedures, cabling, and the spooling and re-spooling of reacted strands.

2 Experimental

2.1 Strand Fabrication

Specifications of the three types of MgB₂ multifilamentary strands that were fabricated by HTR are given in Table I. Optical images of the strand cross sections are shown in Figure 1. One of the PIT strand, PIT-54, was fabricated using the continuous tube forming and filling (CTFF) process [11] in which the precursor powder mixture is continuously dispensed onto a Nb strip prior to its being formed into a tube. This filled Nb tube was then placed in a Cu₁₀Ni tube to form a filament. These filaments, along with a central Cu₁₀Ni filament, were bundled and placed in a Cu₁₀Ni tube and the composite was drawn to 0.55 mm. In the fabrication of the other PIT strand, PIT-36, the same process was used, except that (i) the filled Nb tube was placed inside a Cu tube, (ii) a Cu central filament was used, (iii) a Monel® tube was used as the outer sheath and (iv) the strand was drawn to 0.83 mm. The AIMI strand, AIMI-18, had 18 sub-filaments, each of which made by placing a Mg rod along the axis of a B-power-filled Nb tube. These filaments, along with a central Nb filament, were bundled and placed inside a Nb/Monel® bi-layer tube. The composite was then drawn to an OD of 0.83 mm. Commercial Mg powder, 99%, 20–25 µm particle size, was used for the PIT strands. The B powder, manufactured by Specialty Metals Inc., was mostly amorphous, 50–100 nm in size. Undoped B was used in PIT-54, and 2% C pre-doped

B was used in PIT-36 and AIMI-18. For all strands, a heat treatment of 675 °C for 60 min under flowing Ar was applied. Before heat treatment, a standard twisting process applied to the PIT-54 strand provided twist pitches, L_p , of from 10 mm to 100 mm. Bending of PIT-36 and AIMI-18 was applied after the HT.

2.2 Transport Property Measurements

Critical current density, J_c , and n -value measurements were made on samples of strand about 5 cm long, voltage tap separation about 5 mm, at 4.2 K in transverse magnetic fields B of up to 10 T. The J_c criterion was 1 $\mu\text{V}/\text{cm}$. Reported here is the “non-barrier J_c ” defined as the critical current normalized to the area within the Nb tube (the barrier). This measure, different from the layer J_c cited in materials optimization studies, is more appropriate for conductor performance comparisons. Two sample probes were used: (i) a “short-sample probe” in which the sample was immersed in pool-boiling liquid He, (ii) a “varitemp probe” in which the sample was cooled by exchange gas and a heater enabled variation of temperature up to 30 K [13,25].

2.3 Twist and Bend Testing

Twist-tolerance tests were performed on pre-reacted PIT-54. Bend-tolerance tests were performed on PIT-36 and AIMI-18 strands after reaction. The strands were straight during reaction. Afterwards they were uniformly bent at room temperature, a set of arc-shape dies made with G-10 material being used to control the bending process, Fig. 2. Assuming the neutral axis was at the geometric centre of the strands, the maximum bending strain is given by:

$$\text{Max Bending Strain} = R_w / (R_w + R_B) \quad (1)$$

where R_w is the strand radius and R_B is the radius of G-10 die. The values of R_B and the corresponding maximal bending strains experienced by a 0.83 mm OD strand are listed in Table II. The strand was then allowed to relax mechanically, mounted onto the J_c test probe (without straightening even if deformation remained), cooled to temperature, and measured. In contrast to previous bend test measurements in which application of bending in-situ after cool down or the application of bending at room temperature and its retention during cool down [20, 21, 23], the present tests were designed to evaluate the tolerance of the strand to bending during react-and-wind coil fabrication or cable winding followed by operation at cryogenic temperatures.

3 Results of the Measurements

3.1 Transport Properties of the Starting Strands

Figure 3 represents the 4.2 K transport $J_c(B)$ s for (a) strand PIT-54 and (b) strand PIT-36. The temperature dependence of transport $J_c(B)$ for strand AIMI-18 is presented in Figure 3 (c). At 4.2 K, 5T, the J_c of PIT-36 was more than three times that of PIT-54 the increase being attributable to the effect of C doping. The 4.2 K, 5 T J_c s of PIT-36 and AIMI-18 were fortuitously about equal. However, increases in the latter’s MgB_2 -layer area would lead to superior performance, as discussed in [13].

At 20 K, the non-barrier transport J_c of AIMI-18 is $\approx 10^4 \text{ A/cm}^2$ at 5 T. Even at 25 K a transport J_c of 10^4 A/cm^3 was obtained at 2 T. It is worth noting that these results for a multifilamentary AIMI strand offer promise for applications in the 20 K regime. A modified Eisterer percolation model [24–26] was used to fit the J_c vs B curves for various temperatures, Figure 3 (c). Figure 3 (d) displays vs the n vs B curves at various temperatures. The n -value is observed to follow

$$n \propto e^{-m \times B} \quad (2)$$

where m is a fitting parameter [12, 13, 27–29].

3.2 Influence of Twisting on Transport Properties

Figure 4 (a) shows the J_c - B behaviors of a series of twisted PIT-54 strands. PIT-54, with an OD of 0.55 mm and a sub-filament size of $\sim 20 \mu\text{m}$ (left in Figure 1), was twisted to pitches of from 100 mm to 10 mm, a range useful for practical applications. Over the whole range of L_p values this strand exhibited no degradation in J_c at any field. Even the strand with a twist pitch as small as 10 mm exhibited $J_c(B)$ behavior very close to that of the untwisted control. The n -values vs B for the PIT-54 are plotted in Figure 4 (b), where little influence of L_p on n -value is seen over the range investigated.

3.3 Influence of Bending on Transport Properties

Figure 5 shows the 4.2 K transport results for PIT-36 in response to initial bending strains of 0 to 0.4% followed by release in terms of: (a) $J_c(B)$ as function of applied field up to 10 T; (b) the relative change of $J_c(B)$ as function of bending strain, defined as

$$\Delta J_c(B) = \frac{J_c(B, \text{bend}) - J_c(B, \text{unbend})}{J_c(B, \text{unbend})}; \quad (c) \text{ } n\text{-value vs bending strain at various } B \text{ up to } 10 \text{ T.}$$

Figure 5 (b) shows that bending strains of up to 0.4% have only a small influence ($< 5\%$) on $J_c(B)$ is very small ($< 5\%$).

4 Discussion

4.1 Influence of Twisting

The $J_c(B)$ degradation of twisted four-core MgB_2 strands, made by an *ex situ* and *in situ* process, was reported by appeared at $L_p < 71 \text{ mm}$ [14]. With $L_p = 30 \text{ mm}$, a 30% J_c (5 T) decrease after twisting was also observed in the *in situ* strand and a 60% degradation in J_c (5 T) for the *ex situ* strand [14]. Ková *et al* reported no degradation in $J_c(B)$ of a 19-filamentary MgB_2 strand with $L_p > 25 \text{ mm}$, claiming the high resistance to twisting was due predominantly to reinforcement by a stainless steel outer sheath [16, 17]. Compared to the MgB_2 strands in [14–17], PIT-54 has a smaller OD, a smaller sub-filament size, and a higher filament-number. Our observations of no degradations of $J_c(B)$ and n -value with $L_p = 10 \text{ mm}$ augur well for the damage-free reduction of AC loss by twisting in MgB_2 strands.

4.2 Influence of Bending

A linear increase in J_c of PIT MgB_2 strands response to increasing tension has been reported by Ková [18] and Nishijima[21]. Over 10% increases in 4.2 K J_c obtain at 6.5 T with 0.4%

– 0.6% strain [19] and at 10 T with 0.54% strain [21], while the compression has been reported to reduce the J_c performance of MgB_2 [21]. In our case, the outer portion of the MgB_2 strand is in tension while the inner portion is under compression during bending. The bending-strain independent $J_c(B)$ of PIT-36 can be an average of the effect of tension and compression. Katagiri [23] reported a field-independent critical bending strain of a single-core PIT strand to be 0.45%. Although our PIT strand is 36-core, our results are quite consistent with Katagiri's observation. The n -values of PIT-36 are insensitive to bend strain at field up to 10 T, as seen in Figure 5 (c). All these three figures indicate that the transport properties of PIT-36 are independent of bending strain up to 0.4% at 4.2 K and 4–10 T.

Figures 6(a), (b), and (c) show that this AIMI-18 does exhibit some measurable bending strain sensitivity, in particular: (i) Figure 6(a) indicates a small shift in $J_c(B)$ in response to strain; (ii) Figure 6 (b) shows J_c to be weakly bend-strain dependent. For example at 8 T J_c rises by about 12% from 6.7 to 7.5×10^4 A/cm² at 0.3% strain, drops to the starting value at 0.5% strain and continues to decrease to 6.2×10^4 A/cm² at experimental bend-strain limit of 0.6%; (iii) Figure 6(c) depicts the strain dependence of n -value at selected applied fields; only in fields of 8 T and above is any approximation to a trend observable. The $J_c(B)$ is relatively unchanged at 0.1% bending strain, which is probably due to the absence of plastic deformation at this stage; an increase in J_c with a further increased bending strain up to 0.3% indicates the strand is plastically deformed and the internal strain state of the MgB_2 filaments starts to release; a further increase in bending strain gradually decreased the $J_c(B)$ is due to the breakage of MgB_2 grain connection. All these bending strain influences on $J_c(B)$ are field-independent. Compared to the results of PIT-36, AIMI-18 represents a much larger pre-strain, which cannot be completely cancelled by the negative effect from the compression portion. Nishijima [21] found the reversible tensile strain of a single-filamentary IMD strand at 4.2 K and 10 T to be 0.67%, and the value for a single-core PIT strands to be 0.54%. Ková [22] showed the reversible tensile strain of a four-filamentary IMD strand to be 0.43% at 4.2 K and 5 T, higher than the value of four-filamentary PIT strand (0.38%). An increase in the transport performances of AIMI-type strand of up to 10% as the bending strain increased to 0.3% was followed by a monotonic decrease with further increases in strain.

5 Summary

The starting transport properties of PIT-54 and PIT-36 were measured in applied fields of up to 10 T at 4.2 K and in the case of AIMI-18 at temperatures up to 30 K. The 4.2 K, 5 T, non-barrier J_c s of PIT-54, PIT-36, and AIMI-18 were, respectively, 0.6, 2.0, and 2.0×10^5 A/cm². Given that PIT-36 and AIMI-18 have the same strand ODs and non-barrier 4.2 K, 5 T J_c s but differing non-barrier areas for critical current normalization (13% and 28%, respectively), implies that AIMI-type strands have the potential, on an equal non-barrier-area basis for twice the J_c performance of PIT. AIMI-18 has a J_c of 10^4 A/cm² at 20 K and 5 T, as well as at 25 K and 2 T. Such a J_c for a multifilamentary AIMI strand augurs well for applications in the high temperature regime.

PIT-54 twisted to pitches of 100 mm down to 10 mm (duplicating a practically useful range) showed no degradation in $J_c(B)$; even the strand with an L_p as small as 10 mm exhibited

$J_c(B)$ behavior very close to that of the untwisted control. Furthermore, little influence of L_p on n -value is seen over the range investigated. The absence of degradations in $J_c(B)$ and n -value with $L_p = 10$ mm enable a reduction in loss without damaging the transport properties of MgB₂ strand.

In examinations of bend strain tolerance bending strains of up to 0.6% (corresponding to a bend of radius 63.1 applied to a 0.8 mm OD strand) were applied at room temperature to PIT-36 and AIMI-18. After bend relaxation the transport properties were measured at 4.2 K in applied fields of up to 10 T. For PIT-36 both $J_c(B)$ and $n(B)$ were found to be independent of bend strain within the above limit. AIMI-18 can be regarded as bend-strain tolerant up to about 0.5% strain. For example at 8 T J_c rises from 6.7 to 7.5×10^4 A/cm² at 0.3% strain, drops to the starting value at 0.5% strain and continues to decrease to 6.2×10^4 A/cm² at experimental bend-strain limit of 0.6%. The strain dependence of n -value shows considerable scatter.

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Figure 1.
Optical cross section images of PIT-54, PIT-36 and AIMI-18 after reaction for 675 °C/60 min.

Figure 2.

Apparatus used to apply a bending strain at room temperature. The wire to be bent is run between two pulleys, with weights used to apply a constant force. A shaped piece of G-10 is then raised until the bent wire lays along its whole curvature. The G10 piece is then retracted and the wire removed.

Figure 3.

Transport properties of the starting strands: J_c vs B for (a) PIT-54, (b) PIT-36, and (c) AIMI-18. The n -value vs B of AIMI-18 is also represented in (d). Lines in (c) are fitting curves based on a modified percolation model for MgB₂ strands [25]. Lines in (d) are fits to $n \propto e^{-m \times B}$.

Figure 4.

4.2 K Transport properties of PIT-54 in response to twist pitch: (a) J_c vs B , and (b) n -value vs B .

Figure 5.

4.2K transport results for PIT-36 in response to applied bending strain plus release: (a) J_c - B behavior, (b) the relative change of J_c vs bending strain, and (c) n -value vs bending strain at various B .

Figure 6.

4.2K transport results for AIMI-18 in response to applied bending strain plus release: (a) J_c - B behavior, (b) the relative change of J_c vs bending strain, and (c) n -value vs bending strain at various B .

Table I

Specifications and properties of the strands

Name	Filament No.	Chemical Barrier	Outer sheath	Central filament	B source	Mg:B ratio	OD, mm	% area under Nb barrier	$J_c(4.2K, 5T)$ $10^5 A/cm^2$	Test
PIT-54	54	Nb	Cu10Ni	Cu10Ni	SMI	1:2	0.55	14.5	0.6	twist
PIT-36	36	Nb	Monel®	Cu	2%C SMI	1:2	0.84	12.9	2	bend
AIMI-18	18	Nb	Monel®	Nb	2%C SMI	1.37:2	0.83	28.2	2	bend

Table II

Bending radius and bending strain for a 0.8 mm OD strand

Bending radius, R_B , mm	Maximum bending strain, %
Inf..	0
379.3	0.1
180	0.2
125.5	0.3
94.6	0.4
76.3	0.5
63.1	0.6