The Influence of Wire Bending and Wire Diameter on Transport Critical Current Density in Small MgB₂ Superconducting Coils for Applications in Multi-Section Coils

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Abstract

This article presents the impact of MgB₂ wire bending and diameter on transport critical current density and irreversible magnetic field of a resultant coil. Unreacted MgB₂ wires 500 mm in length and 0.63 or 0.83 mm in diameter have been used in the fabrication of small diameter (14 mm) superconducting coils. The coils were subsequently annealed under isostatic pressure of 1 GPa for 15 min at 700 °C and 725 °C. Our results indicate that larger wire diameter, higher annealing temperature, and bending lead to slight reduction of critical current density and irreversible magnetic field in the coil.

Keywords Coils · Critical current density · MgB₂ wires

1 Introduction

The first research on superconducting coils was conducted by Heike Kamerlingh Onnes [1, 2]. These studies indicated that the winding of superconducting wires reduced the critical current density [1]. Degradation of performance was due to defects introduced to the structure of the superconducting material during the winding process, e.g., damage in the connections between the grains. A few of these defects can be removed by annealing the unreacted MgB₂ wire post winding [3–6]. Our previous research showed that annealing under high isostatic pressure of coils made with 10% SiC-doped MgB₂ wire with large bending diameters leads to similar J_c as that in a straight wire [7]. The small difference in J_c is due to two factors. Firstly, thermal treatment under high isostatic pressure improves the uniformity and density of the MgB₂

material, leading to an increase in the number of connections between grains and the density of pinning centers [8, 9]. The second factor is the large amount of admixture [7], which also improves the homogeneity and density of the MgB₂ material [7]. Moreover, the large amount of admixture effectively increases J_c at low temperatures (4.2 K) [10].

Uchiyama et al. [11], Wang et al. [12], and Gajda et al. [13] showed that wire diameter reduction as the result of cold drawing and constant annealing temperature increases critical current density, irreversible magnetic field, pinning force, and n value and does not decrease the critical temperature and dominant pinning mechanism. However, Xu et al. indicates that a significant reduction of wire diameter causes a decrease of J_c [14].

A multi-section coil comprises of several coils, namely, a main coil and compensating coils. The main coil is made with wires of a much larger diameter than that of the compensation coils. This allows for better homogeneity of the magnetic field in the multi-section coil. The magnetic field with high homogeneity is necessary for many applications, e.g., magnetic resonance imaging (MRI) [15]. Currently, superconductor wires are most often used in MRI.

The purpose of this article is to analyze the impact of bending of unreacted wire on a small former, annealing under high isostatic pressure, and reduction of wire diameter on critical current density, Nb barrier, and structure of MgB₂ material for applications using multi-sectional coil construction.

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2 Wire Preparation and Measurements Condition

Coils were wound with wires of in situ MgB_2 (the starting composition of the material is 1.1 Mg + 2B powder mixture). The MgB_2 wire was not doped, with 18 filaments, outer sheath of Monel, copper filamentary matrix, niobium barrier, and fill factor of about 15%, sized to a diameter of 0.63 mm and 0.83 mm. The unreacted MgB_2 wires were made by Hyper Tech Research Inc. in OH, USA [16]. Coils were made from 500 mm length of wire. Coils have inner diameter (d_c) of 14 mm and were single layered. MgB_2 wires were wound on a steel barrel. The coils and short wire samples were annealed in 1 GPa (HIP), at temperatures of 700 °C and 725 °C, for 15 min. Details are provided in Table 1. HIP was performed in Ar gas in the Institute of High Pressure, Warsaw, Poland [17]. Critical current (I_c) measurements were made in Institute of Low Temperature and Structure Research PAS in Wrocław [18]. Critical current (I_c) of the short wires (distance between voltage contacts—10 mm) and coils (distance between voltage contacts—100 mm) was measured with a four-probe resistive method at a temperature of 4.2 K for a constant current from 0–150 A. I_c was determined on the basis of 1 $\mu\text{V}/\text{cm}$ criterion. Both types of samples have been measured in perpendicular magnetic field. The irreversible magnetic field was determined from the Kramer analysis ($J_c^{0.5} \cdot B^{0.25}$ formula) [19]. The Nb barrier soundness was tested by field sweep [18] and temperature sweep method [20]. The microstructure investigations using EDX were performed with SEM FEI Nova Nano SEM 230 in the ILT and SR PSA in Wrocław and Zeiss microscope (high resolution low-energy) in IHPP PAS Warsaw, using the secondary electron SE mode.

3 Results

EDX results (Fig. 1) show the compositions of the HIP-ed MgB_2 wires wound on the coil and short straight HIP-ed MgB_2 wires. The small amount of Na, C, and Ca observed

in the microstructure of the MgB_2 material is from the preparation of wire samples for SEM analysis. The more relevant comparison is the Mg content, which is quite high and similar for both types of wire. This suggests that there is no major breach in the Nb barrier and the HIP process yielded MgB_2 material of high purity.

SEM results (Fig. 2) show that the microstructure of MgB_2 wires wound on the coils and that of MgB_2 short straight wires obtained with the same HIP parameters is similar. Figure 2a, b, c and d show that after the HIP process, there are no cracks in the winding and superconducting MgB_2 material. Moreover, we do not see the reaction between Nb barrier, copper, and MgB_2 material.

Measurements made by using the field sweep [18] and temperature sweep method [20] show that bending of unreacted MgB_2 wires on a small size (14 mm) former does not create cracks in the Nb barrier.

The J_c obtained for short straight undoped MgB_2 wire sample A2 (diameter 0.83 mm) is about 10% higher than that of coil—sample A1 (Fig. 3a). The J_c results obtained for short straight undoped MgB_2 wire (samples B2 and C2, diameter 0.63 mm) are higher by about 25% than that of the same wire wound on the coils (samples B1 and C1) (see Fig. 3b). The increase of annealing temperature causes an increase of J_c in high magnetic fields (Fig. 3b) for short straight wires and those wound on the coil, especially for lower wire diameter ($d = 0.63$ mm). The straight wire with smaller diameter (sample B2, Fig. 3b) has lower J_c than that of straight wire with a larger diameter (sample A2, Fig. 3a) of about 10%. Comparing obtained J_c results for wires with diameter of 0.83 mm wound on the coil (sample A1) and J_c of wound wires with diameter 0.63 mm (sample B1) on the coils, it can be seen that the wire bending of the smaller diameter leads to reduction in J_c of 15%.

The Kramer analysis shows that the bending of the MgB_2 wire slightly reduces B_{irr} by 0.5 T (straight wire, 14.5 T, compared with bent wire, 14 T). On the other hand, the higher annealing temperature for wires with the 0.63 mm diameter leads to a slight increase in B_{irr} by about 4% in wires and 2% in coils. In addition, the Kramer analysis indicates that wire bending and diameter reduction from 0.83 to 0.63 mm reduces B_{irr} by 10%.

Table 1 Technical parameters of 18 filaments MgB_2 wires with Nb barrier, Monel sheath, and 15% fill factor

Sample	Annealing temperature [°C]	Annealing time [min]	Pressure [GPa]	Diameter (mm)
A1—coil	700	15	1	0.83
A2—straight	700	15	1	0.83
B1 coil	700	15	1	0.63
B2—straight	700	15	1	0.63
C1 coil	725	15	1	0.63
C2—straight	725	15	1	0.63

Fig. 1 EDX analysis performed for **a** sample A1, undoped MgB_2 wire extracted from the coil ($d = 0.83$ mm) with coil ($d_c = 14$ mm), and **b** sample A2, undoped MgB_2 straight wire ($d = 0.83$ mm)

4 Discussion

We know that cold drawing of in situ MgB_2 wire elongates Mg grains [21] and increases the number of dislocations. The smaller Mg grains and higher number of dislocations increases the rate of reaction during heat treatment. This causes creation of larger grains and smaller number of connections. These factors reduce J_c in the wires with the diameter of 0.63 mm as compared with the wire of larger diameter (0.83 mm).

Our SEM study for wires with a diameter of 0.63 mm shows that bending does not create damages in wires, which would reduce J_c . When, the bending diameter is the same, there should be less strain (stress) with a smaller diameter wire. The lower J_c in bending of wire with smaller diameter (0.63 mm) caused by bending Mg grains of smaller thickness and longer, and strains. This accelerates the growth of grains and reduces the number of connections between grains and consequently reduces J_c in the coils of wires with a diameter of 0.63 mm.

The heat treatment process at temperature of 725 °C and 1 GPa pressure increases J_c in high magnetic fields because

Mg is in the liquid state at this temperature [22]. The reaction in liquid state of Mg causes a higher degree of shrinkage of material [23]. This factor creates stresses (dislocations) in the MgB_2 material structure. Gajda et al. shows that dislocations and strains create pinning centers, which increase J_c in high magnetic fields [24].

Comparing our results with the results in ref. [7], it can be concluded that a large (10%) SiC doping significantly reduces the negative impact of bending and reduction of wires diameter on the critical parameters of the coils.

Based on our results, it can be concluded that the main superconducting coils in multiple section coils should be made with large diameter wires. These coils should be heated at high temperature (700 °C) to ensure high critical parameters of the coil. In contrast, compensating coils should be wound with smaller diameter wires and heated at low temperature (e.g., 570 °C [9]). This leads to high critical parameters in the compensating coils. High J_c in the main and compensating coils allows for high magnetic field with high uniformity in a multi-sectional coil. This leads to cost reductions in the production of multi-sectional superconducting coils.

Fig. 2 **a** (longitudinal section), **c** (longitudinal section), and **e** (cross section) show the microstructure of sample C1 (coil, $d = 0.63$ mm) and **b** (longitudinal section), **d** (longitudinal section), and **f** (cross section) show the microstructure of sample C2 (straight, $d = 0.63$ mm)

5 Conclusions

The J_c of short undoped MgB_2 wire of 0.83 mm diameter was similar to the J_c of the coils wound with the same wire. The

results indicate that a smaller wire diameter, bending, shape, and size of Mg grains and annealing at higher temperature under high isostatic pressure lead to the reduction of J_c in the coils. This can be explained by the resultant Mg grains

Fig. 3 Transport J_c - B curves for the HIP-ed undoped MgB_2 wires measured on the coil and on the short straight sample for **a** 0.83 mm diameter and **b** 0.63 mm diameter

of smaller size from wire drawing, and that bending accelerates the rate of synthesis reaction. The SEM results show that the microstructure of the wires wound on the coils and that of short straight wires is very similar. In both cases, HIP appears to increase the density of the material. Moreover, the cold bending of unreacted MgB_2 wire did not damage the Nb barrier. Our results show that for better performance in a multi-sectional MgB_2 coil, main coil should be heated at higher temperature and compensation coils at lower temperature.

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