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Rational design of MgB_2 conductors toward practical applications

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ABSTRACT

We report the research progress that has been made on developing rational MgB_2 superconducting conductors toward practical applications. Owing to the poor performance of the critical current density (J_c) of bare MgB_2, various techniques have been developed to overcome this obstacle. Among these, chemical doping has proved to be the most effective way to enhance the superconducting properties, such as J_c and the irreversibility field (B_{irr}). More than a hundred different forms of dopants have been investigated over the past 13 years. Among these, the most effective dopants have been identified to be silicon carbide, carbon, and malic acid. The best results, B_{irr} of 22 T and J_c of 40,000 A cm^{-2} at 4.2 K and 10 T, have been reported for malic acid treated MgB_2 conductors, which have matched the benchmark performance of commercial low temperature superconductor wire such as Nb–Ti. This work will review and discuss the progress on MgB_2 conductor development over the past few years at the University of Wollongong and Hyper Tech Research, Inc.

1. Introduction

The first commercial superconducting wire was developed about 52 years ago, in 1962. Even now, the majority of superconducting magnets are made of niobium titanium (Nb–Ti), or niobium tin (Nb_3Sn), wires [1–4], and are operated in a liquid helium (LHe) environment. The continuous soaring price of LHe has increased the demand of alternative cryogen more than ever for various applications of the superconductors. From soon after the discovery of its superconductivity in 2001, MgB_2 has triggered a great deal of interest in the research community [5], due to possibility of cryogen-free, solid nitrogen (SN_2), or mixed cooling operation. The simple crystal structure, high critical temperature (T_c) of 39 K, high critical current density (J_c), large coherence length, and transparency of grain boundaries to current flow of MgB_2 make it special [6]. These properties of MgB_2 further offer the promise of some key large-scale applications [7]. As can be seen in Fig. 1, using MgB_2 conductor will open up a new domain of applications for superconducting direct current (DC) magnets, especially below 5 T and 20 K. During the past 13 years, MgB_2 has been fabricated in various forms, including single crystals, bulk, thin films, tapes, and wires [8–13]. In particular, enormous efforts have been directed towards the improvement of J_c and achieving a fundamental understanding of MgB_2 materials [14–17]. We have reported J_c values for MgB_2 as high as 40,000 A cm^{-2} at 10 T and 4.2 K, and 40,000 A cm^{-2} at 5 T and 20 K [18]. This gives proof that the performance of MgB_2 conductors can compete with and even exceed that of the conventional low temperature superconductor (LTS) Nb–Ti. The J_c of pristine MgB_2 drops rapidly, however, with increasing external magnetic field due to its low upper critical field (B_{c2}) and weak pinning strength. To take advantage of its higher T_c of 39 K, enhancement of B_{c2} and improvement of its in-field performance are particularly important. Attempts to enhance the B_{c2} and flux pinning have been made by using a number of techniques, including addition, substitution, and various mechanical processing techniques [13,16,19,20]. In this article, we will give a brief review of our research activities based at the University of Wollongong (UOW) and Hyper Tech Research Inc. (HTR) on materials processing and characterization of rational superconducting MgB_2 conductors.

2. Continuous tube forming and filling (CTFF)

Fig. 2 contains a schematic illustration of continuous tube forming and filling (CTFF), a novel technique for the fabrication of MgB_2 conductors. This technique has been developed by HTR to prepare long-length MgB_2 wires [7,21]. In this process, a continuous metal strip (niobium (Nb), iron (Fe), etc.) is used as the inner barrier. As this metal ribbon enters and moves through the tube shaping dies,

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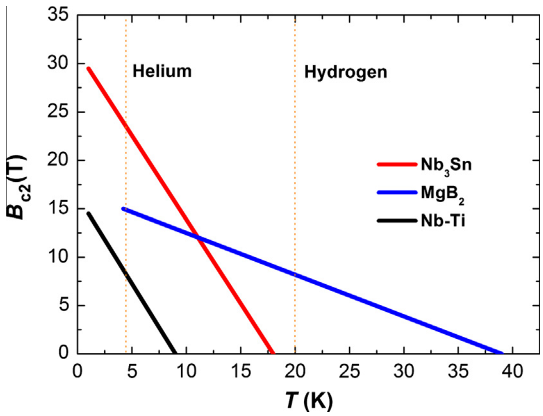

Fig. 1. Comparison of B_{c2} of low temperature superconductors (Nb–Ti and Nb_3Sn) and MgB_2.

they gradually form it into a 'U' shape. After the composite powder (magnesium (Mg) and boron (B)) is inserted, the closing dies gradually close off the tube. After the tube has been closed, it passes through subsequent dies to reduce the diameter to a fine wire (i.e. 0.832 mm). So far, HTR has 10 years of manufacturing development experience on various MgB_2 composite conductors. These conductors have been designed by keeping manufacturability in mind. The processing steps are designed to be commercially viable. HTR regularly manufactures composites in lengths over 10 km [22]. Even though long lengths are no limitation, wire quality over lengths >10 km is still not consistent, either due to issues with the manufacturing process or the starting material [21–24]. The strands are mainly made from *in situ* powders, with Nb or Fe barriers, a copper (Cu) stabilizer, and a Cu-nickel (Ni) outer sheath (called "Monel"), and there are different filament numbers from 7 to 61 in the final multi-filamentary conductor. Heat treatment (HT) is typically in the 700 °C range for 20–40 min. For reacting and winding the wire, S-glass braid is normally coated on the surface of the conductor as an insulator. Very recently, HTR has been working on increasing the filling factor to 30%, which would increase the critical current (I_c) towards practical applications.

3. Effects of amorphous and crystalline boron powders on conductor performance

The '*in situ*' method has been used successfully to make MgB_2 wires and tapes [7]. In most cases, both high purity crystalline or

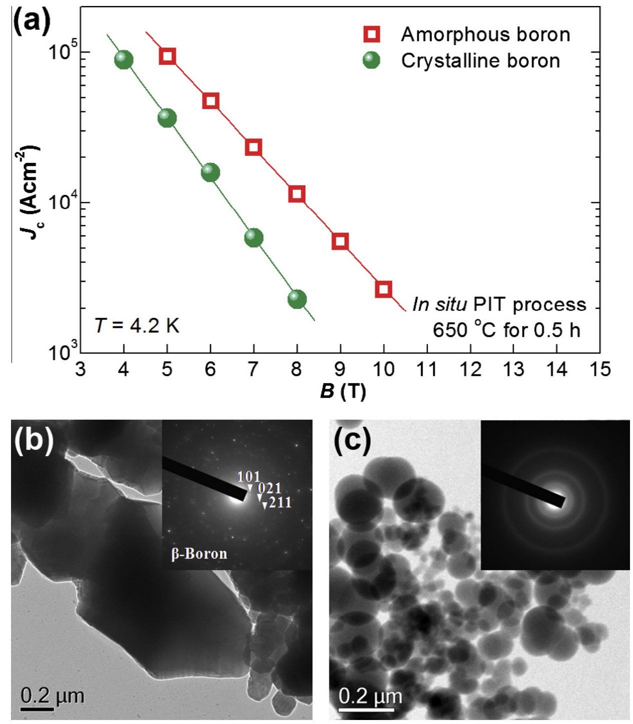

Fig. 3. (a) Comparison of J_c in MgB_2 wires made from different B powders with amorphous and crystalline phases. TEM images of (b) crystalline and (c) amorphous B powders. Insets to (b) and (c): corresponding selected area electron diffraction (SAED) patterns.

amorphous B powder and small size Mg are used to make the MgB_2 conductor [25]. If this wire is to be applied in an industrial application, however, the costs of the raw materials will be significantly increased, and this needs to be taken into serious consideration [26]. The material cost could be decreased significantly by using low-grade precursors. High purity (98–99%) amorphous B powder is about ten times more expensive than low purity (95–97%) crystalline B powder [26]. Fig. 3(a) shows a comparison of J_c in MgB_2 monofilament wire made from different B powders with amorphous and crystalline phases. Crystalline B (Fig. 3(b)) is known to have the β-rhombohedral structure, which is quite stable, even after high temperature sintering [27]. Thus, it is hard for it to fully react with Mg powder to form MgB_2. A relatively long sintering time or high sintering temperature is obviously required.

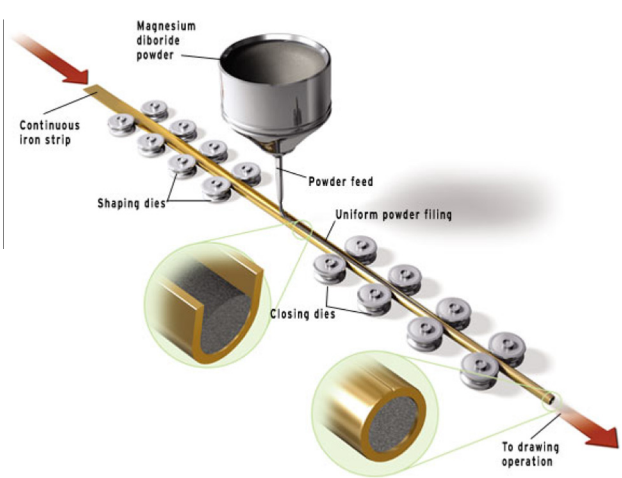

Fig. 2. Schematic illustration of CTFF process.

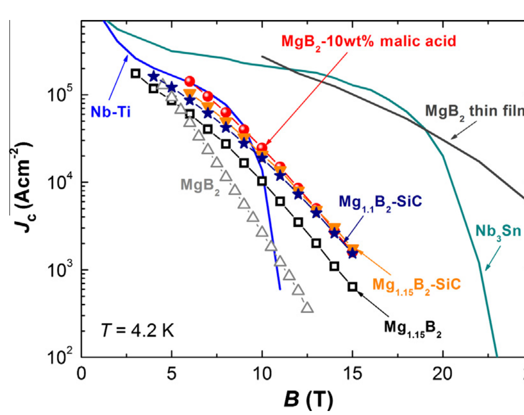

Fig. 4. Comparison of J_c–B characteristics at 4.2 K of malic acid treated wire with those of other commercial MgB_2 wires fabricated by HTR. The malic acid treated MgB_2 wire was sintered at 600 °C for 4 h. The J_c was about 25,300 A cm^{-2} at 4.2 K and 10 T.