

## Magnetic and transport properties of HTS MgB<sub>2</sub> wires

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**Abstract.** Critical current  $I_c$  and magnetization  $M$  of industrial MgB<sub>2</sub> tape and wire were measured in order to estimate their suitability for production of liquid helium free cryomagnetic system. Samples were subjected to bending with different diameters  $D_b$  and critical current was measured at temperature  $T = 4.2$  K in magnetic fields up to 10 T. The dependences of the critical current on the diameter of the bend  $I_c(D_b)$  were found and used for optimization of liquid helium free cryomagnetic system. The magnetization of the wire was measured by a vibrating sample magnetometer at temperatures  $T = 4.2, 10, 15, 20, 25$  K in magnetic fields up to 14 T. It was found that the magnetization curve  $M(H)$  is influenced by ferromagnetic response of the metal matrix. Ferromagnetic contribution had been taken into account and magnetization loops caused by the diamagnetic contribution of the superconducting phase were extracted. Dependencies  $I_c(T)$  and  $I_c(H)$  were obtained from the data.

### 1. Introduction

Great attention is paid to MgB<sub>2</sub> superconductor because of its unique properties such as relatively high critical temperature, big coherence length and low anisotropy [1]. Low cost of magnesium and boron powders makes that material attractive for industrial application. Nowadays a lot of technological innovations in wire production allows to achieve high critical current values and good mechanical properties are developed. The most promising applications of MgB<sub>2</sub> wires are the cable industry and the development of MRI (magnetic resonance imaging) machines. By virtue of the application features, MRI coils should have large diameter (tens of centimeters) and provide uniform magnetic field. Using MgB<sub>2</sub> wire at liquid helium temperatures allows us to achieve the required parameters. However, there are problems concerned with creation of high-current leads and winding the coils bended with a small diameter (few centimeters). It is known, that the characteristics of wires and tapes based on MgB<sub>2</sub> are affected by bending deformations [2]. Starting with a certain critical diameter, the critical current starts to degrade. However, the literature provides little information about change of characteristics with decreasing diameter of the bending deformation. In our previous studies [3] for ex situ MgB<sub>2</sub> wires and tapes produced by Columbus Superconductor it was shown, that the critical current decreases with bending diameter decrease. Even for diameter of  $D = 100$  mm the bending deformation leads to drop of the critical current. Depending on amplitude of external magnetic field the critical current for  $D = 30$  mm is in the range 39 - 57% of that for  $D = 100$  mm. At the same time,

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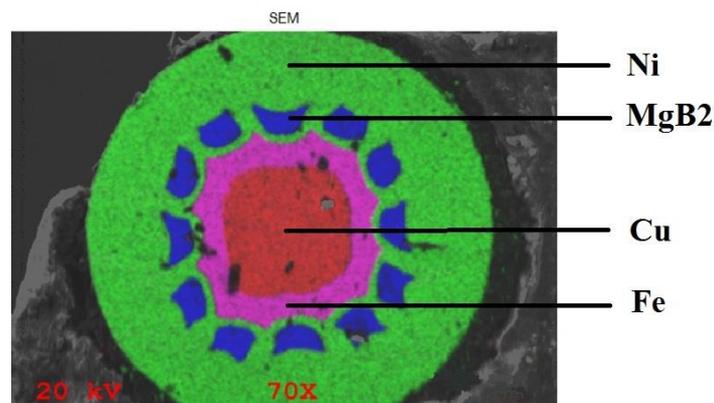


despite the significant degradation of the critical current, our sample did not break down and kept superconducting properties even at such small bending diameter.

In present work the MgB<sub>2</sub> wires are considered within the scope of the creation of liquid helium free cryomagnetic system with operating temperatures of 4.2 - 30 K and a small diameter warm bore (4-10 cm). To create MgB<sub>2</sub> coil with small diameter the “wind and react” technology is usually used [4]. That avoids bending deformation, and hence degradation of the wire, since the formation of the superconducting phase takes place under annealing of already formed coil. However, this technology requires a complex process of homogeneous heat treatment in the furnace and does not allow pre-study the characteristics of the wire. Thus, we decided to explore the possibility of creating a coil from an industrial superconducting wire by “react and wind” method. For this purpose, at different temperatures the magnetization curves of for MgB<sub>2</sub> wire and tape were measured along with isothermal ( $T = 4.2$  K) dependences of critical current on the mechanical bending of various diameters. The magnetization was measured using a vibrating sample magnetometer and allowed us to calculate  $I_c(T)$  dependence. The data obtained can be used to optimize the cryomagnetic system.

## 2. Samples

In this paper we investigated the flat tape with the size of 3.5 x 0.6 mm and round wire with diameter  $d = 1$  mm, commercially manufactured by Columbus Superconductor by PIT ex-situ technology. Number of filaments in the metal matrix is equal to 12 and the filling factor of MgB<sub>2</sub> is 10.7% for the wire and 12.2% and for the tape. The filling factors were calculated as the ratio of MgB<sub>2</sub> filaments area to the total cross-section area on photographs presented in Figure 1. There is a copper filament in the center of the wire, encased in an iron shell. Filaments of MgB<sub>2</sub> are enclosed in a matrix of Ni.



**Figure 1.** Photograph of cross-sections of ex situ MgB<sub>2</sub> wire

## 3. Mechanical bending

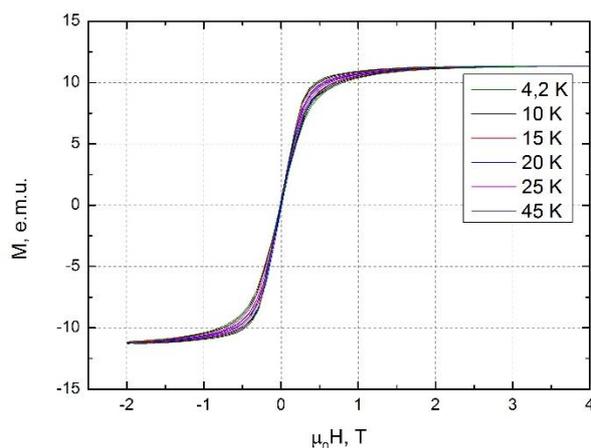
In order to determine the dependence of the critical current of tapes and wires on the diameter of the mechanical bending,  $V-I$  characteristics were measured at temperature of liquid helium. Measurements were carried out for bending diameters  $D = 30, 40, 60, 70, 80, 90, 100$  mm in magnetic field applied perpendicular to the direction of the current. A detailed description of the measurement methods and analysis of experimental data is given in [3]. It is shown that with increasing external magnetic field, the critical current density decreases exponentially. However, the superconductivity of the tape does not disappear even for minimal bend diameter of  $D = 30$  mm, but  $I_c$  is only 44% of that for  $D = 100$  mm. For comparison, significant degradation of the critical current of the 2G HTS tapes begins only when the bending diameter is less than 15mm for both compressing and tensile bending strain [5].

#### 4. Magnetic measurement

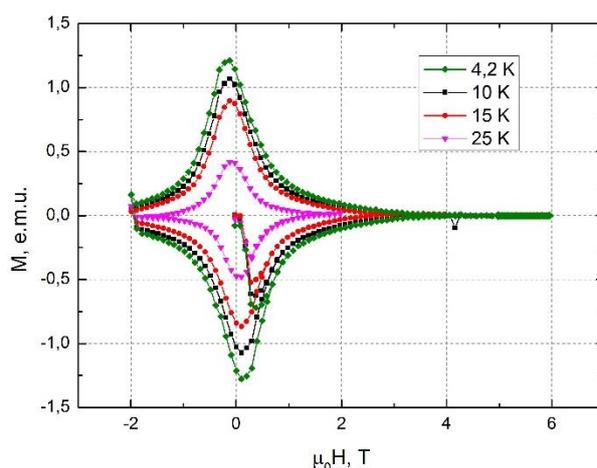
To study magnetic properties of wires and tapes the vibrating sample magnetometer was used [6]. Measurements were carried out in magnetic field applied perpendicular to the wire axis and the plane of the tape (force configuration). Heat-exchange helium gas was used to stabilize temperature of the sample.

To increase amount of superconducting material and amplitude of the measured signal we used two parallel pieces of the wire with equal lengths. Measurements were carried out at temperatures  $T = 4.2; 10; 15; 20; 25; 45$  K. The necessity of measurements above the critical temperature ( $T_c \approx 39$  K) was caused by presence of strongly pronounced reversal ferromagnetic contribution to magnetization from Fe and Ni contained in shell. As seen in Figure 2, the magnetization curves saturate near  $H = 3$  T, so expand field to greater values is not advisable. Because of the loops symmetry, measurements of the curves in negative fields were restricted by  $-2$  T.

The superconductive diamagnetic contribution to the magnetization in the temperature range 4.2 – 25 K was obtained by subtracting the curve measured at  $T = 45$  K. We expect that variation of the ferromagnetic contribution at  $T < 45$  K is not essential since these temperatures are small in comparison with the Curie temperatures for Fe and Ni. Magnetization of  $MgB_2$  changes drastically in low field, see Figure 3. Thermomagnetic instability of  $MgB_2$  and magnetic field deployment provide significant measurement error in low fields, so part of magnetization curve in vicinity of zero field was obtained as a result of polynomial fitting.



**Figure 2.** Magnetization loop of the wire. External field was applied perpendicular to the wire axis.



**Figure 3.** The superconductive hysteretic contribution to the magnetization loop for temperatures  $T = 4.2 - 25$  K. External field was applied perpendicular to the wire axis.

The dependence of critical current on external magnetic field and temperature (Fig.4) was calculated by the formula

$$I_c(T, H) = I_c(4,2) * \frac{\Delta M(T,H)}{\Delta M(4,2,H)} \quad (1)$$

where  $I_c(4,2)$  is the critical current in zero field at  $T = 4.2$  K and  $\Delta M(T, H)$  is width of the magnetization curve hysteresis.

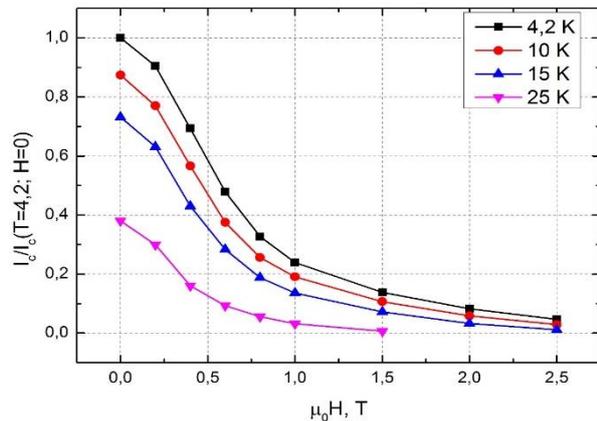
The field and temperature dependences of the critical current are shown in Figures 4 and 5.

As seen from Figure 4, for all temperatures the zero-field points deviate from  $I_c(H)$  dependences at higher fields. So the polynomial fitting represents only lower estimate of low-field magnetization and the critical currents can be significantly increased if the thermomagnetic instability is suppressed.

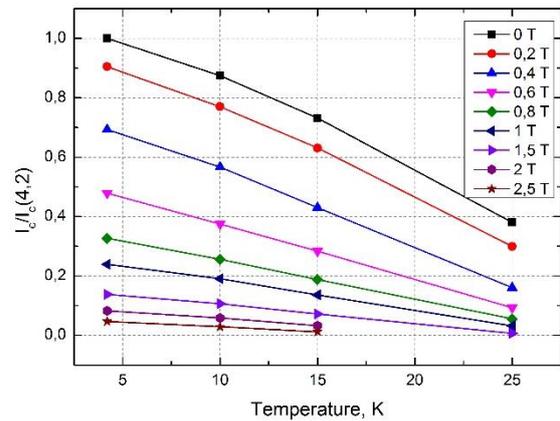
Critical current drastically decreases with increasing external magnetic field (5 times drop with field increasing from 0 T to 1 T) for all temperatures. A similar behavior of critical current occurs with

increasing temperature at persistent external magnetic field (drop up to 25% for temperature rise from 4.2 K to 15 K).

The data obtained allow one to calculate load curves and maximal magnetic field for a solenoid of given sizes, to estimate its operating temperature and to choose optimal construction of a cryomagnetic system.



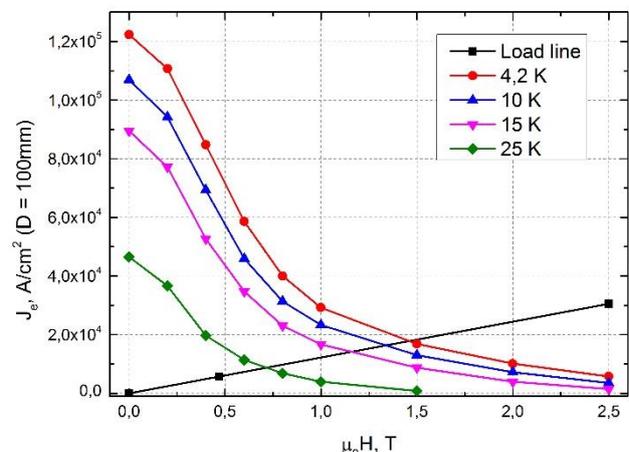
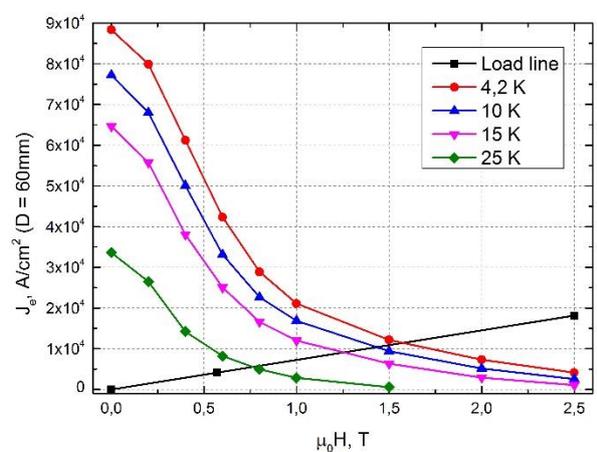
**Figure 4.** Dependences of critical current on external magnetic field obtained at different temperatures. The data are normalized on  $I_c$  value measured at  $T = 4.2$  K and  $H = 0$  T



**Figure 5.** Temperature dependences of critical current obtained for different magnetic field. The data are normalized on  $I_c$  value measured at  $T = 4.2$  K and  $H = 0$  T

In present work we consider two solenoids with inner diameters of  $D_{in} = 60$  and 100 mm, height  $h = 140$  mm, length of the winding wire  $l = 400$  m and expected fill factor of winding  $k = 0.8$ . Load lines, calculated for field constants of the solenoids of 13.94 mT/A and 8.28 mT/A respectively, are shown in Figure 6. For  $D_{in} = 60$  mm the maximal value 1.45 T of the magnetic field  $H_m$  at the solenoid center is achieved at temperature of 4.2 K for current  $I = 104$  A. Temperature increase up to 10 K or 25 K leads to decrease of  $H_m$  by 9%, or 51%. For  $D_{in} = 100$  mm the  $H_m$  value 1.35 T is achieved at 4.2 K for  $I = 163$  A. Temperature increase up to 10 K or 25 K leads to decrease of  $H_m$  by 10%, or 52%.

Thus, solenoid of  $D_{in} = 60$  mm produces greater field for the same length of wire. In addition, essentially lower current is required for field producing. Increase of operating temperature to 10 K leads to small (within 10%) operating field decrease, so a cryocooler with low power can be used for liquid helium free cryomagnetic system to reduce its cost.



**Figure 6.** Field dependences of the critical current density obtained for  $MgB_2$  wire under bending deformation with  $D_{in} = 60$  mm (left) and 100 mm (right). The straight lines are load lines for solenoids

with the above-mentioned bore diameters.

## 5. Conclusions

Despite the fact that the current-carrying capacity of bended MgB<sub>2</sub> wires significantly degrades, it remains suitable for the production of solenoids with small enough internal diameters. Maximal magnetic field calculated for solenoids of diameters  $60 \text{ mm} \leq D \leq 100 \text{ mm}$  exceeds 1 Tesla. The solenoid of smaller internal diameter produces greater field and its operating current is lower. An increase of the operating temperature up to 10 K leads to field reduction only by 10%. In such conditions, a low-power cryocooler with operating temperature of about 10 K can be used for cooling the cryomagnetic system.

## Acknowledgments

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