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# AC losses of single-core $MgB_2$ wires with different metallic sheaths

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ABSTRACT

AC losses of single-core $MgB_2$ superconductors with different metallic sheaths (Cu, GlidCop, stainless steel and Monel) have been measured and analyzed. These wires were exposed to external magnetic field with frequencies 72 and 144 Hz and amplitudes up to 0.1 T at temperatures ranged from 18 to 40 K. The obtained results have shown that applied metallic sheath can affect the measured AC loss considerably. In the case of GlidCop and Stainless Steel a negligible small effect of metallic sheath was observed. Strong contribution of eddy currents has been found in the wire with well conductive copper sheath. In the case of Monel sheath, the hysteresis loss of magnetic sheath is dominated and AC loss of $MgB_2$ core is practically not visible.



## 1. Introduction

Due to low cost, critical temperature above 20 K and industrial production in km lengths [1] $MgB_2$ is a promising superconductor not only for DC but also for AC applications. Superconducting transformer, fault current limiter [3] and power cable cooled by liquid hydrogen are the examples of $MgB_2$ at industrial frequencies [2–4], where AC loss is one of the key issues. AC applications need low AC losses, which in the case of filamentary $MgB_2$ wires have usually two main components: hysteresis losses and the coupling losses between the filaments. It is well known that hysteresis loss can be decreased effectively by the reduction of the filament size. Filament's twisting and/or application of resistive barrier around the filaments offers an efficient reduction of coupling loss. But, it has been already shown that $MgB_2$ wires with very thin filaments and/or with too short twist pitch have also low critical current density [5–6]. Additional losses (e.g. eddy current loss and hysteresis loss in magnetic material) can be generated in metallic components used for composite $MgB_2$ wire. Therefore, not only properties of $MgB_2$ filaments are important, but also proper sheath material is needed for low loss conductors. $MgB_2$ superconductors are considered recently also for direct drive wind turbine generators [7–8], where the losses generated by AC magnetic fields must be removed by the cooling system and has to be considered in the design of efficient and secure generator [8]. Recently, several contributions on AC losses in $MgB_2$ have been presented [9–11]. The AC loss in $MgB_2$ wires with nonmagnetic sheath and variable architecture has been analyzed [9]. Decoupling effect in twisted wires and transposed cables [10] and AC losses of high current density $MgB_2$ wires made by IMD process have been also presented [11]. Magnusson et al. have shown the coupling current and hysteresis losses in Ti sheathed $MgB_2$ superconductors and described the coupling currents by phenomenological approach [12].

The main aim of the present study is to demonstrate the effect of applied metallic sheaths on AC losses in single-core $MgB_2$ wires without contribution of coupling currents.

## 2. Experimental

### 2.1. $MgB_2$ conductors

The set of four single-core $MgB_2$ wires with different outer sheaths was selected for the magnetization AC loss measurements. Fig. 1 shows the cross sections of these wires named **1Gl** (a), **1SS** (b), **1Cu** (c) and **1Mo** (d) which composition and sizes are described more in details by Table 1. The sample **1Cu** was made by IMD process [13], **1Gl** and **1SS** samples by in-situ powder-in-tube (PIT) technique [14–15] and **1Mo** by the so-called continuous tube filling and forming (CTFF) technique [16]. Wire **1Gl** is equipped by Nb diffusion barrier and GlidCop AL-60 (copper reinforced by Aluminum Oxide) material as outer sheath. Sample **1SS** has also Nb barrier, but outer sheath of stainless-steel 316 L. Pure copper protected by Ti was used for wire **1Cu** and wire **1Mo** is sheathed by standard Monel 400 alloy (containing Ni ∼ 63.0%, Cu 28–34% and also Manganese < 2.0%) separated from $MgB_2$core by Nb foil.

### 2.2. AC loss measurements

Measurement system is based on the calibration free method [17] and cooling of the sample by two-stage cryocooler Sumitomo CNA-11

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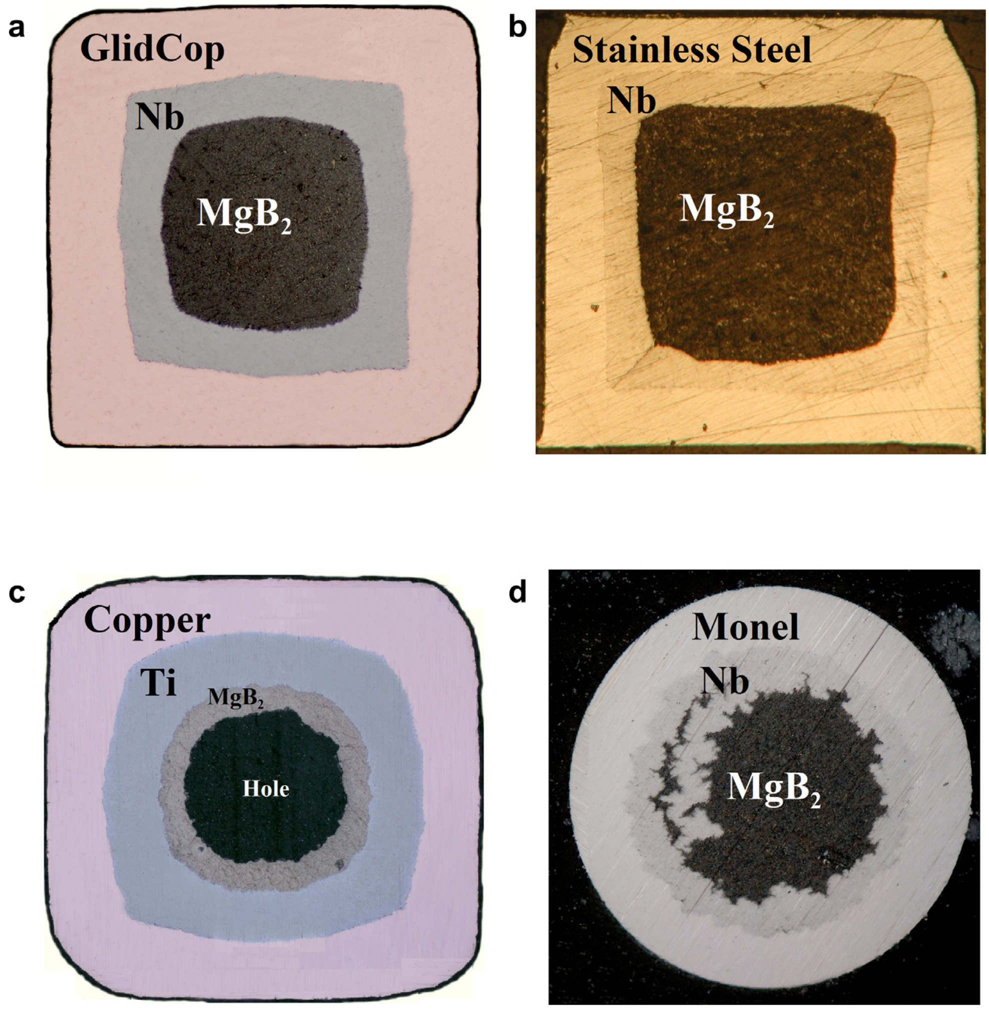


**Fig. 1.** Cross-sections of compared single-core $MgB_2$ wires: 1Gl (a), 1SS (b), 1Cu (c) and 1Mo (d).

**Table 1**
Basic properties of examined single-core $MgB_2$ wires.

| Sample | 1Gl | 1SS | 1Cu | 1Mo |
|---|---|---|---|---|
| Length [mm] | 50.74 | 50.5 | 50.60 | 70.21 |
| $I_c$ (6T, 4.2 K): [A] | 57.7 | 64.5 | 60 | 27 |
| Outer size [μm] | 1208 | 1490 | 1106 | 498 |
| Core. size [μm] | 542 | 970 | 582 | 252.6 |
| Barrier. size [μm] | 812.5 | 1117.5 | 830.95 | 357.9 |
| Sc. Area [$mm^2$] | 0.29 | 0.94 | 0.113 | 0.14 |
| Sheath material | GlidCop | Stainless steel | Cu | Monel |
| Barrier material | Nb | Nb | Ti | Nb |
| Made by | PIT, in-situ | PIT, in-situ | IMD | PIT, CTFF |

with cooling power 0.1 W at 4.2 K. The measured wire is placed inside the sample holder made of well thermally conductive Aluminium-nitride BNP-2 ceramic material. High power audio amplifier with current transformer and a system of capacitance compensation are used for magnet charging. To determine inductive and loss part of measured signal dual channel Lock-in amplifier was used. Described apparatus is able to measure AC losses with high precision and sensitivity at minimal temperature 15.5 K and in external field from $10^{-4}$ T up to $10^{-1}$ T at frequencies 72 and 144 Hz [11].

## 3. Results and discussion

Fig. 2(a) shows the temperature dependence of magnetization AC losses in one cycle per volume of superconductor measured for sample **1Gl**. Variable external field from 14 to 70 mT and frequencies 72 Hz (full symbols) and 144 Hz were applied. As one can see, AC losses have very low values at low temperatures (18–20 K) due to high current density and low field penetration into the sample. AC loss increases with temperature which is attributed to decreased current density and subsequent deeper penetrating of magnetic flux into $MgB_2$ at each AC magnetic field. AC loss maximum represents the full penetration of the magnetic flux ($B_{fp}$) at given temperature. Further increase of temperature causes that AC loss is lowered due to $J_c$ reduction with temperature. AC losses are not more measurable in the normal state when critical temperature is reached. Fig. 2(a) presents only hysteretic character of AC losses in agreement with the theoretical assumption for single-core superconductor, which is confirmed by the same results measured at frequency 72 and 144 Hz. Some small frequency dependence close to critical temperature can be possibly attributed to some eddy current loss in GlidCop sheath.

Fig. 2(b) shows the magnetic field dependences of AC loss in sample **1Gl** at temperatures 28, 29 and 30 K compared with theoretical assumption using an ellipse model [18]. The slope of presented $Q(B)$ measured at 28 K bellow 25 mT corresponds approximately to $B^3$. The shape of $Q(B)$ at 28 K changes the tendency from $B^3$ to $B^1$ at about 25 mT, which represents the point of full penetration $B_{fp}$. It means that above this field, sample **1Gl** is fully penetrated by magnetic flux and AC loss is proportional to applied field $B$. Similar change of $Q(B)$ is observed at 29 and 30 K, but at lower $B_{fp}$ ~10 and ~4.5 mT, respectively. Differences between measurement and calculation can be explained by the real cross-section of superconducting core, which has not exact circular shape used for our calculations. Nevertheless,