# Bi-2212 round wire development for high field applications

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**Abstract.** Oxford Superconducting Technology (OST) has been continuously improving Bi-2212 round wire performance because of its potential for application in high-field magnets (> 25 T). We focused on Bi-2212 wire configuration design, filament densification and reducing carbon and hydrogen contamination to improve the engineering critical current density ($J_E$). Several wire configurations have been developed to meet different wire diameter and operating current requirements. The swaging, cold isostatic pressing (CIP) and over-pressure heat treatment processes have been demonstrated to effectively increase Bi-2212 filament mass density in the final wire and result in high performance over long length. The $J_E$ values exceeding 550 A/mm$^2$ at 4.2 K, 15 T have been achieved on the CIPed 1 m long sample using a 10 bar over-pressure (OP) heat treatment. The twisted Bi-2212 wire significantly reduced ac loss without the critical current degradation.

## 1. Introduction

It is well known that $Nb_3Sn$ superconducting magnets cannot be applied in the magnetic field higher than 25 T because of the limit of its upper critical field ($B_{c2}$). High $T_c$ superconductor $Bi_2Sr_2CaCu_2O_{8-x}$ (Bi-2212) wire has demonstrated many attractive features, such as high irreversibility field ($B_{irr}$ > 100 T), isotropic electromagnetic performance, solenoid layer winding, and compatibility with conventional cabling and strand insulation methods. All of these advantages make it easy to adapt the well established $Nb_3Sn$ technology and make Bi-2212 one of most promising materials to enable superconducting magnets > 25 T range [1-8].

One of the largest challenges for large scale application of Bi-2212 wires is the current-limited by filament porosity. Therefore, OST focuses on improving $J_c$ and $J_E$ in long length Bi-2122 round wires by exploring wire processing conditions to reduce the porosities. In this paper, we report our recent results from densifying Bi-2212 core filaments, developing new wire configurations and applying the twist on Bi-2212 round wires.

## 2. Experimental

Bi-2212/Ag round wires were fabricated by the traditional powder-in-tube and multifilament restack techniques and the detail is described in our earlier papers [3, 7]. In this work, Nexans granulate powder with the optimized composition of $Bi_{2.17}Sr_{1.94}Ca_{0.89}Cu_{1.98}O_x$ was used for all wire fabrication. Bi-2212/Ag wires were heat treated using a partial melt-solidification process in 1 atmosphere flowing oxygen. The over pressure heat treatment was performed at Applied Superconductivity Center of National High Magnetic Field Lab (ASC-NHMFL) as described in other publication [8].

The critical current, $I_c$ was measured using the four-probe transport method with a 0.1 μV/cm criterion at 4.2 K under applied field up to 15 T. The barrel sample is typically 1.2 m in wire length and the voltage tap spacing is 72 cm. Bi-2212 core density was calculated by measuring sample weight, volume and HTS core fill factor. Wire diameter was measured with a laser micrometer. Microstructures were examined using optical and scanning electron microscopies. The quench experiments and detailed microscopy study were performed at ASC-NHMFL [5, 6]. Hysteresis losses were measured in a quantum design physical property measurement system, equipped with a vibrating sample magnetometer at National Institute of Standards and Technology (NIST).

## 3. Results and Discussion

### 3.1. Optimum wire configuration and size

One purpose of the present work is development of various sized wires with optimum $J_E/J_c$ values for satisfying the different magnet design and operating current requirements. As well known, the peak $J_c$ and $J_E$ in Bi-2212/Ag wires depend on the final filament size and the best $J_E$ falls in the filament size ~15 μm, demonstrated in our early study using 0.8 mm 85x7 configuration wires [3]. Therefore, in order to produce a large diameter wire, we have to increase the filament number to make the filament size close to 15 μm. The 19, 37, 85 or 121 mono-core hex rods were stacked in the sub-billets. 18 or 36 sub-billet hexes plus 1 Ag central rod hex were bundled and restacked into the AgMg alloy tubes and drawn to a range of final wire diameters from 0.8 to 1.5 mm (referred as 19x36, 37x18, 85x18, 121x18 wires) [9]. Table 1 presents optimized wire size for each configuration. It can be seen that the configurations of 19x36 and 37x18 are most suitable for wire ~0.8 mm, 85x18 for wire ~1.2 mm, and 121x18 for wire ~1.4 mm, respectively. The best $J_E$ values (4.2 K and 15 T) of wires with different configurations versus number of filaments of sub bundle are also listed in table 1. All the samples with the similar fill factor of ~25% were made by OST standard process [3] without further densification and heat treated on barrel (1.2 m in sample length). It can be observed that the as-drawn wire performance strongly depends on the number of filaments in sub elements. It is probably due to their difference in the bridges between filaments within the sub elements. By microstructure study, the filaments within a sub bundle normally merge together after final heat treatment, while not linking across sub bundles [10]. In the as-drawn wires without core densification, because of a large amount of porosity, the bridges between filaments may play an important role for filament continuity, resulting in a better wire performance for higher filament number wire configuration.

**Table 1.** Bi-2212 round wire configurations, optimum wire diameters and their peak $J_E$ values in as-drawn wires. All samples were heat treated using OST standard HT profile in 1 atmosphere oxygen.

| Wire configuration (filament number in sub x number of sub bundle) | Fill factor (%) | Optimized wire diameter (mm) | Peak $J_E$ value (A/mm$^2$, 4.2 K, 15 T) in as-drawn wires |
|---|---|---|---|
| 19 x 36 | 24.0 | 0.8 | 195 |
| 37 x 18 | 24.8 | 0.8 | 240 |
| 85 x 18 | 25.2 | 1.2 | 315 |
| 121 x 18 | 25.4 | 1.4 | 320 |

### 3.2. Core densification by swaging, cold isostatic pressing and over pressure heat treatment

In the as-drawn wire, Bi-2212 filament density is about 70% of its theoretical density. The residual 30% void space is distributed within the filaments. During melting treatment, the powder porosity agglomerates in the liquid Bi-2212 of filaments. The C and H from powder and sheath could lead to gas-filled bubble formations [5, 11]. The large bubbles significantly reduce Bi-2212 filament effective cross-section and degrade the long length wire performance. In order to densify Bi-2212 filaments in the as-drawn wire prior to melt heat treatment, swaging or cold isostatic pressing (CIP) processes were applied. By 20% area reduction swaging, the Bi-2212 filament density before heat treatment is increased to nearly 90% of the theoretical density. The cold isostatic pressing at pressures up to 1400 MPa has been used to increase the powder core density. Figure 1 shows the Bi-2212 core density corresponded with CIPing pressure. It is clear to see that the filament density is increased from 71% in the as-drawn wire to > 85% by CIPing with pressure of 650 MPa and > 90% with the pressure of 1200 MPa. As shown in the cross-sections of quenched samples, many large (filament sized) bubbles are observed in as-drawn wire samples quenched from the melt. After 650 MPa CIP, there are fewer bubbles evident during the melting process. The quench study on 0.8 mm 37x18 wire confirms the result [6], showing reduced void fraction in the melted filaments and doubled critical current density.

Figure 2 shows the $J_E$ progress in the recent billets after the core densification. While $J_E$ of ~320 A/mm$^2$ was obtained in the control as-drawn wires, $J_E$ values of ~470 A/mm$^2$ at 4.2 K, 15 T were achieved in the core densified wires after swaging and CIPing processes. Further improvement was realized by using the recently developed over-pressure heat treatment by ASC/NHMFL [8]. This new process prevents wire swelling during heat treatment and improves wire performance significantly. $J_E$ of 550 A/mm$^2$ at 4.2 K and 15 T has been achieved on a 650 MPa CIPed, 1.2 m long sample using a 10 bar over-pressure (OP) heat treatment. Higher performance has been achieved by 100 bar OP process on 5 cm long samples [8]. From this figure, it is also shown highly reproducible Bi-2212 wire performance from billet to billet.

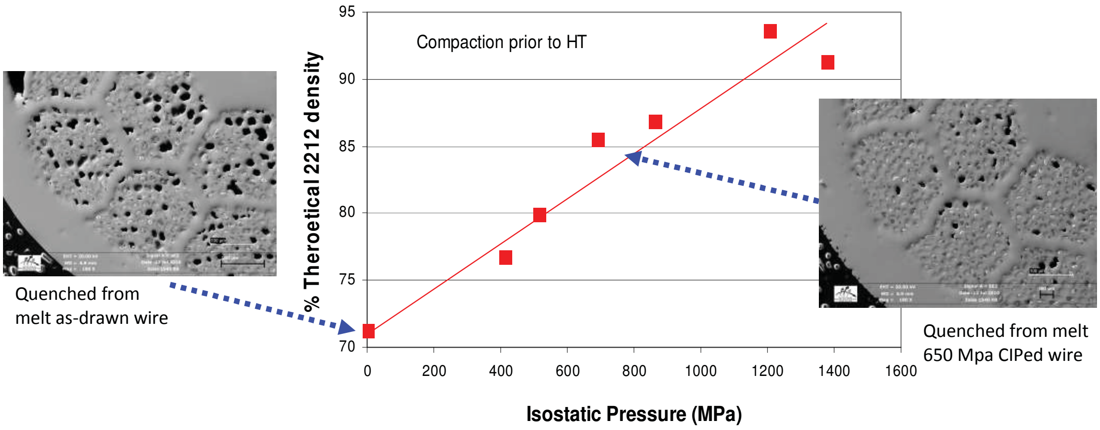


**Figure 1.** Bi-2212 core density as a function of CIPing pressure. The left picture shows the quenched cross-sections from melt samples in as-drawn and the right picture is by 650 MPa CIPing.

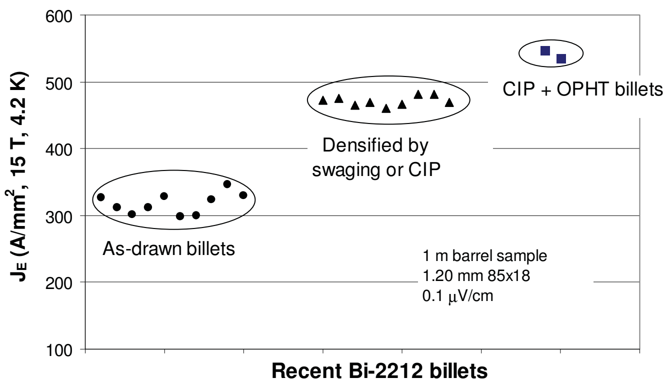


**Figure 2.** $J_E$(B) values at 4.2 K, 15 T for 1 m barrel samples obtained in the recent 85x18 wire billets made at OST by the condition of as-drawn, core densified and over-pressure heat treated at 10 bar, respectively.

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### 3.3. Applying twist on Bi-2212 wires

At OST, we recently applied the twist process on the Bi-2212 wires and found that the twisting process does not deteriorate wire performance even twisting to 12 mm in twist pitch length [9]. Figure 3 shows the direct comparison of the hysteresis losses for the untwist sample and twisted sample with 12 mm twist pitch length of 1.2 mm 85x18 wires. It is clear to see that ac loss is reduced to 50% on the twisted Bi-2212 wire.

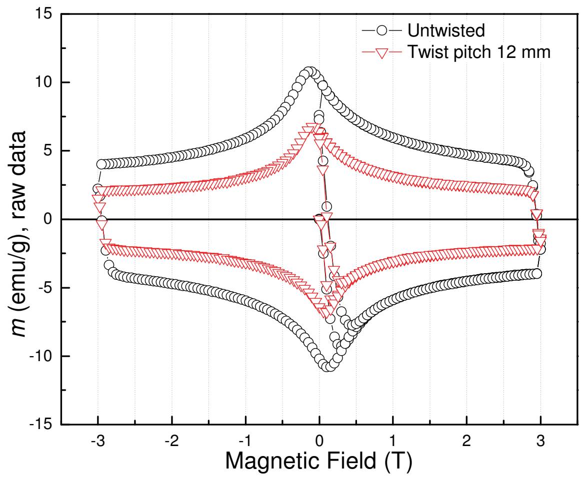


**Figure 3.** The direct comparison of the hysteresis losses between the untwisted and twisted sample with twist pitch length of 12 mm. The samples were made by the same spiral size and heat treatment.

## 4. Conclusions

Bi-2212 round wire performance has been significantly improved recently through filament densification. Filament densification achieved via swaging and cold isostatic pressing (CIP) before the melting process, and over pressure heat treatment during the melting process, have been shown to reduce the porosity and enhance the performance of the Bi-2212/Ag wire. The continued improvements in Bi-2212/Ag wire have enabled demonstration of $J_E$ of over 550 A/mm$^2$ at 4.2 K, 15 T in the 1 meter length wire barrel samples, which provide a great potential for future high field magnet applications. Several filament configurations have been developed to meet different operating current requirements. The twisted Bi-2212 wire significantly reduced ac loss without the critical current degradation.

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