Development of High Superconductor Fraction $Bi_2Sr_2CaCu_2O_x$/Ag Wire for MRI

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***Abstract*—Bi2212 round multifilament wire has good potential for MRI systems designed to operate at 20 K and produce fields greater than 1.5 T. However, Bi2212 conductor is expensive largely due to the costs associated with materials and fabrication. To reduce the cost, we are investigating single restack designs. This approach reduces the silver fraction. It also reduces the amount of processing needed to make the conductor. However, a single restack limits the minimum filament diameter that can be achieved since the strain space is more limited. In this work we evaluated 4 conductor configurations to determine the effects of fill-factor, filament diameter, and s/d on J_e and n value. It was found that a reduction in filament size has a greater effect on J_e and n value than a corresponding increase in fill-factor. Some guidelines for optimization of conductor design are developed.**

***Index Terms*—Bi2212/Ag round wire, high-temperature superconductors, superconducting filaments and wires.**

I. Introduction

MRI MAGNETS are one of the main applications for superconductor wire. MRI magnets must be capable of generating high fields with high stability. The higher the imaging field, the higher is the S/N and the smaller is the feature size that can be imaged. Superconducting MRI magnets typically generate imaging fields of 1.5 T. Currently, units capable of 3 T and 7 T are being sold, and systems that can generate even higher fields are being developed.

MRI magnets must be very stable to produce high resolution images with a high S/N. As a result, MRI systems operate in a persistent mode to achieve high temporal stability. Persistent mode operation without current replenishment requires a conductor with an n-value greater than 20 [1]. The n-value is a measure of the resistive behavior of the superconductor near the superconducting transition. The more abrupt the transition from superconducting to normal resistive operation, the higher is the n-value. The n-value is a function of operating temperature, current and magnetic field, and depends on the quality of the conductor filaments.

NbTi is the material of choice for superconducting MRI magnets. NbTi is a relatively low cost superconductor, and it has excellent electrical properties with a J_e of approximately 300 A/mm^2 at 5 T. It also has good fabrication characteristics. However, NbTi magnets must be cooled to 4.2 K with liquid helium, which adds to the capital cost and operating expense of the MRI unit. Since HTS magnets can be operated at temperatures of 20 K using cryogen free cryocoolers, they offer the potential for systems cost savings.

Of the ceramic HTS materials, Bi2212 has good potential for MRI magnets. It can be produced as a multifilamentary round wire and in long lengths, which are both important features for magnet fabrication. From a magnet engineering perspective, a round or low aspect rectangular wire is preferable to a highly aspected tape, because it is easier to wind and has more isotropic electrical properties. Long lengths reduce magnet fabrication labor and the number of resistive joints that contribute to current decay. Bi2212 can be produced with high J_e and n-values greater than 20 [2]–[4]. In addition to improved imaging capability, high J_e and n-value lead to shorter length wire, fewer resistive splices, and so reduce material and magnet fabrication costs. High J_e also allows higher operating current, thereby reducing the coil size and producing a higher current density in the coil pack.

In spite of its potential, Bi2212 has not been able to compete with NbTi on a cost performance basis. This is largely due to the costs of silver, which is used for the sheath, the oxide powder, and the additional complexity of PIT processing. These factors notwithstanding, Bi2212 could advantageously be used for selected MRI magnets, such as open coil units that operate at high fields, or for units that serve areas where liquid helium is expensive or unavailable.

As part of a comprehensive program to design, build and test an open MRI magnet capable of generating a 1.5 T imaging field, we are exploring ways to reduce the fabrication and materials cost and increase the conductor performance thereby making the conductor more cost effective. To achieve these goals, we are developing a single restack design. This design provides the benefits of lower silver fraction and higher fill-factor compared to double restack designs. High fill-factor should provide additional J_e performance, while the single stack reduces silver content and processing cost.

In this preliminary study on single restack designs, we investigated the effects of fill-factor, filament size and s/d ratio on J_e and n-value. The objective of this work was to identify the parameters that will lead to optimization of the performance of the single restack design in terms of \$/kA-m.

II. Methods and Materials

Four conductor designs were produced for evaluation. These designs were selected to study the effects of filament size, fill

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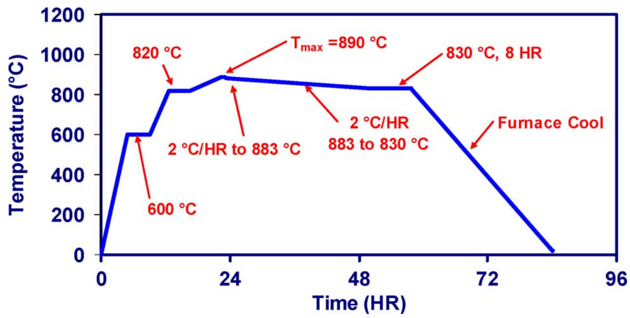

Fig. 1. Temperature-time profile used to melt process short wire samples for I_c measurements. $T\max = 890°C$.

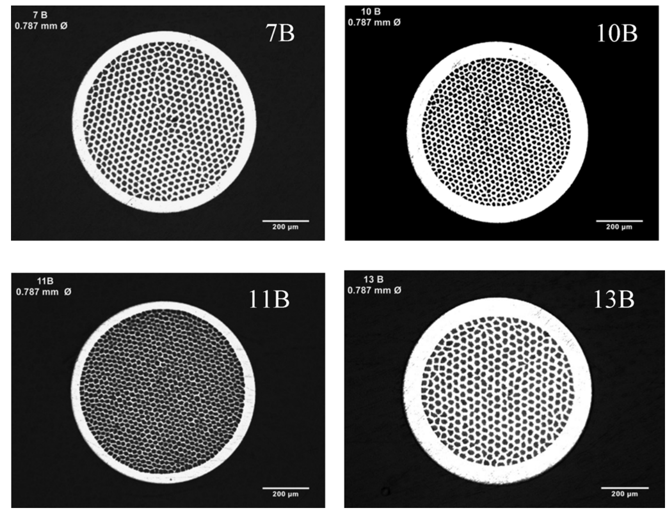

Fig. 2. Unreacted cross-sections of the four conductor design configurations at 0.787 mm diameter evaluated in this study.

factor and filament spacing (s/d ratio). All the conductors were made by standard PIT processing. Bi2212 granular precursor powder was obtained from Nexans Superconductors. The composition, in terms of atomic ratio of the metallic elements, was 2.19 Bi, 1.95 Sr, 0.88 Ca, and 1.98 Cu. The Sr/Ca ratio of this material was 2.22, which was slightly greater than the ratio of 2.17 which has been found to produce high J_c conductor [5]. Monofilaments were made by filling pure silver tubes with powder and cold drawing to the restack size. The monofilaments were restacked in a silver-0.2 wt% magnesium tube. The sizes of the primary silver tube and bundling tube were proportioned to achieve the desired fill factor and s/d. Final filament size was controlled by the restack diameter of the monofilament and the diameter of the bundling tube. All of the conductors were drawn to 0.787 mm diameter. Lengths up to 300 m were produced. Short samples of wire from each conductor were heat treated using the partial melt treatment cycle as shown in Fig. 1. Heat treatment was done in flowing 100% oxygen. T_{max} was 890°C.

I_c measurements were made at 4.2 K and 0, 1, 3, and 5 T using a standard 4 point resistance arrangement to measure V-I on 5 cm samples with a voltage tap spacing of 1 cm and an I_c criterion of 1 μV/cm. B was perpendicular to the wire axis. n values were determined at 0 T from the resistive transition region of the V-I curves by plotting log(V) versus log(I) and using a linear least squares fit to determine the slope. Measurements of filament diameters, fill factors and s/d ratios were performed on polished cross sections of unreacted wire using digital image analysis.

III. Results

Fig. 2 shows cross sections of the unreacted wires at the final size of 0.787 mm, and Table I gives the filament count, fill-factor, average filament size, and s/d ratio. No major differences were encountered in drawing of these wires due to design differences, in contrast to previous studies [6]. A small number of stacking faults in the filament pattern can be seen, but they did not affect drawing behavior.

The single restack design reduces the silver content and the processing steps needed to make a conductor. However, a large number of small filaments must be restacked to produce small diameter filaments. A major fabrication challenge is minimizing stacking faults during bundling of a large number of small diameter filaments, since stacking faults can lead to filament damage. Using a specially developed bundling technique, we found that we could restack a large number of small diameter filaments with a minimum of stacking faults.

TABLE I
Conductor Design Parameters

Conductor	No. Filaments	Fill Factor, %	Filament Diameter, µm	s/d
7B	502	34.7	22	0.41
10B	593	36.2	18	0.35
11B	928	54.7	20	0.25
13B	357	26.8	27	0.28

In looking at the cross sections it is evident that three types of stacking faults are present: interstitial, vacancies and line boundaries. When a vacancy occurs, the surrounding filaments are forced into the void creating a cloverleaf pattern. With an interstitial, the surrounding filaments are displaced in the pattern causing a starfish type structure. Along line boundaries, the filaments are shifted from their normal positions and form a parallel row of filaments. These stacking faults are not a serious problem in drawing and are not likely to affect the performance of the conductor if the frequency of occurrence is a small percentage of the total filament array. Generally, it appears that less than 3 percent of the filaments are affected.

The size of the tubes used for the monofilament and the restack, were proportioned to achieve a specific fill-factor and s/d. For a constant fill factor, the silver content can be proportioned between the monofilament sheaths and the bundling tube, while the spacing between filaments, as given by the s/d ratio, can be adjusted by varying the sheath thickness of the monofilament. For PIT multifilamentary conductors, a smaller s/d generally promotes better filament uniformity and less sausaging due to increased filament support. Conductors 7B and 10B have similar fill factors, but different s/d, while 11B and 13B have similar s/d and different fill factors.

Filament size is controlled primarily by the size of the monofilament in relation to the total amount of reduction of the restack bundle taking into account the degree of tube sinking, which occurs due to powder compaction and the reduction

TABLE II
CRITICAL CURRENTS AND n-VALUES AT 4.2 K AND SELF FIELD

Conductor	I_c (A)	J_e (A/mm^2)	J_c (A/mm^2)	n
7B	265	545	1570	16.0
10B	305	628	1734	23.8
11B	348	716	1313	20.2
13B	134	276	1030	8.2

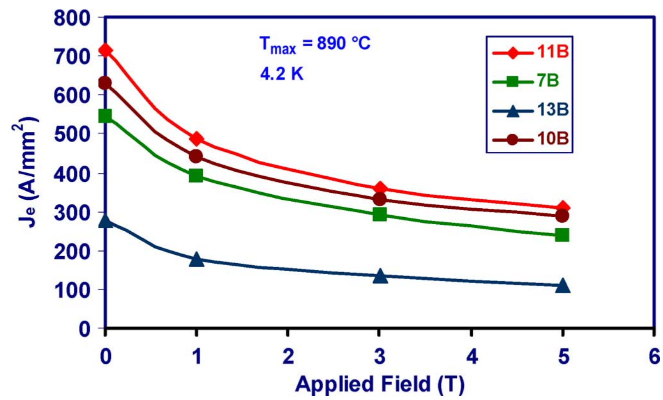

Fig. 3. J_e versus applied field response at 4.2 K for each of the four conductor designs.

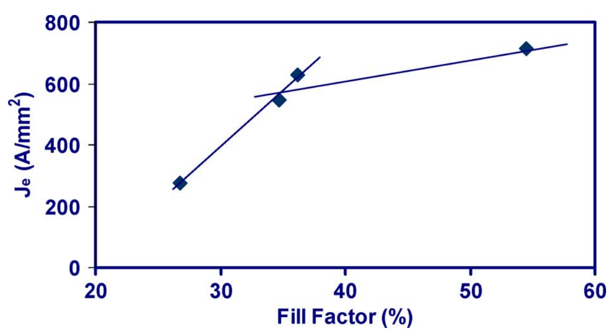

Fig. 4. The effect of fill-factor on J_e at 4.2 K and self-field showing two regimes of behavior.

in void space between filaments in the restack. In a single restack, the strain space is limited by the size of the bundling tube in relation to the final wire diameter. The net result is that filament size is larger than what has been found to be optimum in previous studies [7]–[10].

Table II lists the critical currents and n-values at 4.2 K and self-field. The difference in J_e for each of the conductors is shown in Fig. 3. Conductor 11B, which has the highest fill-factor, has the highest J_e, but it is only slightly higher than 10B which has the smallest filament diameter.

The effect of fill-factor on J_e is shown in Fig. 4. There appears to be two regimes of behavior. For the lower fill-factor regime, the increase in J_e is likely due to a combination of filament size effects and the fill-factor increase, as the fill-factor increased by 35% while J_e increased by more than 128%. For the three wires having the highest fill-factors, the filament sizes are closely grouped. In this regime, there was only a 23% increase in J_e even through the fill-factor increased by 37%.

The J_c values for corresponding filament diameters are shown in Fig. 5. J_c was determined by dividing I_c by the

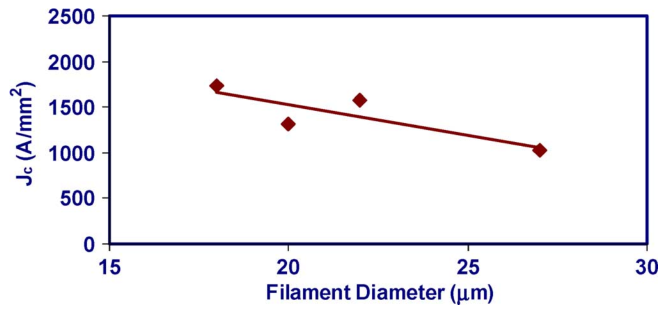

Fig. 5. Relationship between filament diameter and J_c at 4.2 K and self-field.

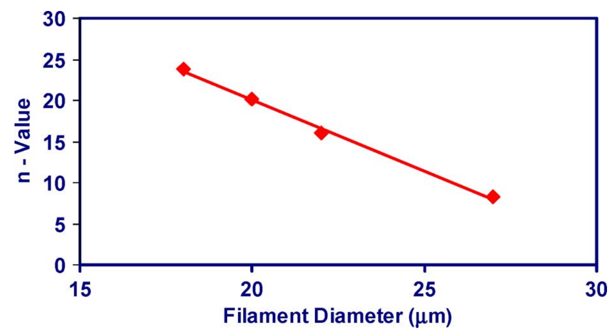

Fig. 6. Relationship between filament diameter and n-value at 4.2 K and self-field.

cross-sectional area of the wire and the fill-factor. As can be seen, there is an inverse correlation between filament diameter and J_c. No minimum or limiting diameter was observed over the size range that was evaluated.

Fig. 6 shows that there is an inverse correlation between filament diameter and n-value, although this effect may also be due to the higher J_c that is produced with smaller filament diameter. There is no apparent effect of s/d on n-values. It was expected that a lower s/d would reduce sausaging, and that the resulting improvement in filament quality would produce a higher n-value. However, comparison of n-values for 10B and 11B shows that 11B, which has the lower s/d, has an n-value that is lower than 10B which has the higher s/d.

IV. DISCUSSION

The results show that further increases in J_e and n-value can be realized primarily through a reduction in filament diameter. It is generally considered that increases in interfacial surface area with smaller filaments leads to more texture after melt processing [11], [12]. Alternatively, smaller filaments could lead to less phase segregation during melt processing and thus more effective formation of high J_c Bi2212 grains [13]. The improvement in n-value as filament diameter is reduced is most likely due to higher J_c filaments.

It has been shown that J_c peaks with a filament size between 15–16 μm, and that with smaller filaments J_c is reduced [3]. The reason for this has not been clearly determined, but it was suggested that the effect was due to sausaging of the filaments. In other studies, J_c increased with filament sizes as small as 10 μm [8]–[10]. Our results show a clear increase in J_c with a reduction in filament size. Bi2212 is very sensitive to small changes in processing conditions [14]. Therefore, it is difficult to extrapolate beyond what the data actually support. However, our results suggest that filaments smaller than 18 μm will produce improvements in J_e. For a single restack conductor, the minimum filament size is limited by the stain space available in drawing to the desired wire diameter, which depends on the size of the billet that can be processed and the diameter and number of filaments that can effectively be restacked. These factors present practical limits to the minimum size filament that can be produced in a single restack conductor.

Increasing the fill factor was found to increase J_e as would be expected, although for the conductors with greater than 37%, fill-factor, the rate of increase in J_e was less than the rate of increase in fill-factor. This effect may be related to a reduction in silver and its effect on whisker formation and the development of interconnects, which has been shown to be important in obtaining high J_c, and may also be related to oxygen diffusion in the silver sheath [5], [15].

The ductility and strength of the wire decrease as fill-factor increases. This can present difficulties in magnet fabrication and increase the strain sensitivity of the conductor. Selection of the optimum fill-factor will require an evaluation of mechanical properties and I_c-strain behavior. For the conductors in this study, it appears that the optimum fill-factor is between 35–40% since increasing the fill-factor to over 50% produces only a marginal increase in J_e.

There was no clear effect of s/d on either J_e or n-values. These results are somewhat unexpected since reducing s/d should improve filament uniformity leading to higher n-value, and increase the amount of interconnects leading to higher J_c. During melt processing, properly processed, high J_c, Bi2212 filaments develop whiskers which form an interconnected filament structure. Whiskers of Bi2212 penetrate the silver sheath and produce numerous interconnects between filaments. These interconnects are thought to be essential to achieving high J_c. The fact that J_e did not correlate with s/d over the range investigated indicates that Bi2212 whisker growth through the silver is sufficiently greater than the characteristic dimension of the silver separating the filaments.

V. Summary and Conclusions

The effects of fill-factor, filament size and s/d have been evaluated for Bi2212 conductors having a single restack design. High fill-factor conductor can be produced without drawing or processing difficulties. Filament diameter has the largest effect on both J_c and n-value. Further improvements in performance could be realized by a reduction in filament diameter below 18 μm, while it appears the optimum fill-factor is in the range of 40%.

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