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Influence of twist pitch on hysteretic losses and transport J_c in overpressure processed high J_c Bi-2212 round wires

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Abstract
Bi-2212 is the only high field, high-temperature superconductor (HTS) available in the macroscopically isotropic, multifilament high J_c round wire (RW) form capable of generating high uniformity fields with minimum-screening current errors. However, the heat treatment that enables impressively high J_c (4.2 K, 30 T) values that can attain ∼5000 A mm^{-2} also produces significant filament bonding (bridging). Filament bridging appears to significantly enhance hysteretic losses of the filaments themselves by coupling neighboring, nominally independent filaments, enabling shielding currents to flow across multiple filaments as though they were one filament of much larger diameter. Wire twisting can be employed to reduce filament-to-filament eddy current coupling losses due to induced currents flowing across the matrix, but twisting is less effective in reducing increased losses from bridging. Here, we compare the twist-pitch dependence of the losses of overpressure processed (OP) high J_c Bi-2212 RWs with partially bridged filaments to those found in OP Bi-2212 RWs with discrete, not-bridged filaments. We show that filament sub-bundles in standard, partially-bridged wires that have some superconducting connections between filaments can exhibit significant coupling (much larger effective filament diameter), but twisting still reduces their hysteretic losses to values close to or below the ITER Nb_3Sn wire loss specification, even though Bi-2212 wires have significantly larger J_c values. Although it has been reported that twisting can reduce wire J_c by damaging filaments, we found no reduction in transport J_c, even for nominal twist pitches of 12 mm in 0.8 mm diameter wires. Evaluation of more-recent, higher J_c Engi-Mat powder wires showed that their reduced filament bridging and improved longitudinal connectivity significantly improved transport J_c and reduced the J_c normalized losses, signaling that J_c can be further improved without commensurate increase in losses. This important result strengthens the argument for production of high field, low loss HTS magnets made with Bi-2212 RWs.

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Keywords: Bi-2212, round wire, high J_c, bridging, hysteretic loss

(Some figures may appear in colour only in the online journal)

1. Introduction

Bi-2212 is the only high field high-temperature superconducting (HTS) material available in high J_c multifilamentary round wire (RW) form [1, 2]. Overpressure processing (OP) has enabled very high J_c in Bi-2212 RWs [1] and with its recently demonstrated J_c (4.2 K, 30 T) ∼5000 A mm^{-2} [3], RW Bi-2212 is a very attractive candidate for high field applications [1, 4]. The round-wire form is very desirable for magnet applications because it allows the conductor to be produced in a macroscopically isotropic, multi-filamentary, low-hysteretic-loss, twisted state that provides high magnetic field uniformity. Hysteretic losses are magnetization losses driven by a time varying external applied field. Inside superconducting filaments, hysteretic losses arise from the viscous motion of flux lines as the field is varied [5]. In multifilamentary Bi-2212 RWs, the changing applied field also couples neighboring filaments electromagnetically, driving eddy currents from filament to filament across the high-conductivity [6, 7], normal Ag matrix. The total loss per cycle Q_t is then given by $Q_t = Q_e + Q_h$, where Q_e is the hysteretic loss contribution of eddy-current coupling and Q_h is the sum of the loss contribution of individual filaments. Twisting is the most common and effective way of reducing Q_e, which can greatly enhance the intrinsic hysteretic losses Q_h of the individual superconducting filaments. Twisting reduces the coupling by limiting the electric field driving the currents to that developed over one half of the twist pitch rather than the whole length of a not-twisted conductor, thus reducing Q_t towards the intra-filament hysteretic baseline Q_h.

The intrinsic hysteretic losses of the individual filaments may also be enhanced by physical inter-filament 'bridging', where grain-to-grain contacts between neighboring filaments provide superconducting paths for screening currents that shield the enclosed matrix [8]. In the presence of bridging Q_t becomes $Q_t = Q_e(\dot{H}) + Q_b(\ln(\dot{H})) + Q_h(\ln(\dot{H}))$, where Q_b is the loss component due to bridging and $\dot{H} = dH/dt$ is the field sweep ramp rate. Transient eddy-current losses Q_e are linearly proportional to $\dot{H}$ [5, 9, 10], whereas Q_b and Q_h which are due to persistent screening currents confined to superconducting loops are proportional to $\ln(\dot{H})$ due to the influence of flux-creep [9, 10]

In the usual configurations of high J_c Bi-2212 RWs, the OP heat treatment compacts the filaments to full density, while also producing some filament bridging. One bridge type is characterized by continuous Bi-2212 grains that grow from one filament into another (figures 1(b) and (f)), as opposed to the more weakly coupled grains that merely impinge on each other as they grow out of one filament into another (figure 1(d)) [11]. Slow cooling from the partial-melt state during the heat treatment produces a texture with long (>50 μm), a-axis aligned grains that are thought to enable the high J_c of Bi-2212 RWs [12]. However, time spent in the melt state also allows liquid Bi-2212 phase to penetrate inter-filament silver grain boundaries, resulting in the strong inter-filamentary Bi-2212 connections shown in figures 1(b) and (f). In usual wires with ∼20 vol.% fill factor, there may be no way of avoiding bridging during the melt stage of the heat treatment without compromising high whole-wire J_c values that require high Bi-2212 fill factor. Thus, it is valuable to understand and characterize the hysteretic losses in modern high J_c Bi-2212 RWs with a view to separate matrix-coupling from superconducting bridging losses, especially in wires produced using the OP that enables the highest short sample J_c (4.2 K, 30 T) in Bi-2212 RWs to date [3]. To this end we compared the losses in two standard wires made with older Nexans and newer Engi-Mat powder to losses measured in a sparse filament R&D wire of low overall engineering current density J_e where strong inter-filament contacts are absent.

Twisting is commonly used to reduce filament-to-filament coupling currents flowing across the normal matrix, and it has also been shown to reduce hysteretic losses in bridged Nb_3Sn [13] and Bi-2212 wires [14]. However, it has also been speculated that twisting reduces transport J_c by damaging the filaments [15]. The aims of these experiments were to characterize hysteretic losses as a function of twist pitch in three different architectures of high J_c OP Bi-2212 RWs so as to determine:

(a) the lowest hysteretic loss per cycle normalized both to wire and superconducting volume that can be achieved by twisting without reducing J_c
(b) the extent to which strongly-coupled, filament-to-filament superconducting bridges contribute to the total losses
(c) the effectiveness of twisting in reducing the total losses of wires having both partially bridged and not-bridged filaments.

2. Experimental details

2.1. Bi-2212 round wires

The details of the Ag–Mg alloy sheathed, 0.8 mm diameter, pure Ag matrix Bi-2212 RWs are given in table 1. All wires were fabricated by Bruker Oxford Superconducting Technology (B-OST) using the Powder-in-Tube technique. Two types of wires were made. Wires with 37×18 and 55×18 architecture had standard filament arrays with closely spaced filaments and a total 2212 fill factor of 23%. A specially made wire was made with a 27×7 architecture that has a sparse filament arrangement. Two 37×18 wires were made (figures 1(a) and (b)), with filament and bundle diameters 14.9 and 120 μm, respectively. Two sets of samples were cut from a 37×18 wire manufactured using lot 77 Nexans granulate powder (billet number pmm100712), and another set from a wire

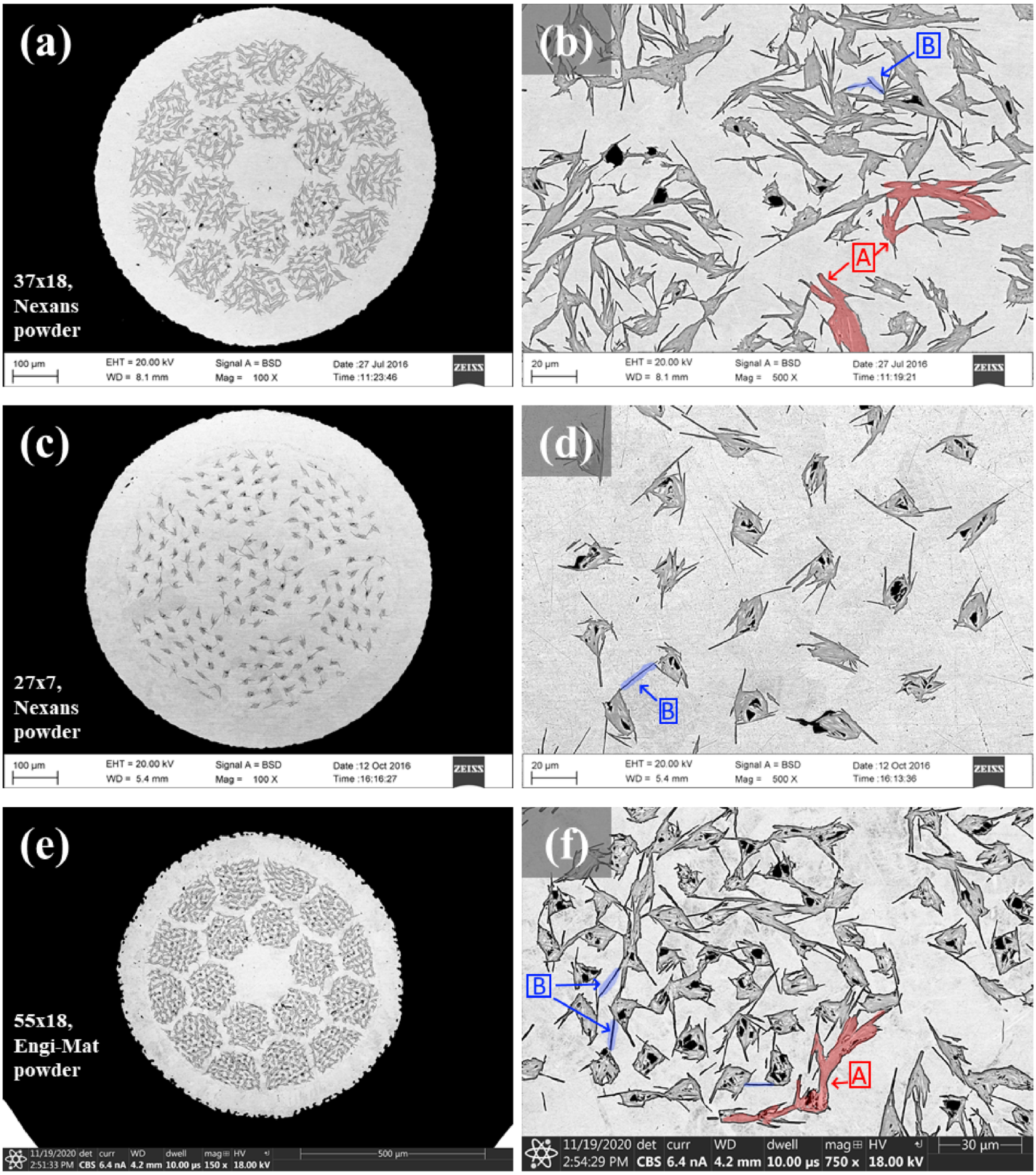

Figure 1. SEM transverse cross-section micrographs of (a) a partially bridged 37 × 18 wire made with Nexans powder, (b) a 37 filament sub-bundle, (c) a not-bridged 27 × 7 wire also made with Nexans powder, (d) a 27 filament sub-bundle, (e) a partially bridged 55 × 18 (Engi-Mat) wire, (f) a 55 filament sub-bundle. All pictures were taken after overpressure heat treatment that essentially fully densified the filaments. The red and blue colorations mark examples of type-A (filament bonding) and type-B bridges (thin outgrowths), respectively.

manufactured using lot 82 Nexans granulate (billet number PMM130723-2). The 55 × 18 wire (PMM180627) was made with a newer, higher J_c Engi-Mat powder (figures 1(e) and (f)) having average filament and bundle diameters of 11.6 μm and 130 μm, respectively. The 27 × 7 wire (PMM080404-2) has filament and bundle diameters of 16.8 μm and 200 μm (figures 1(c) and (d)). This 27 × 7 configuration is achieved by replacing 58 filaments in an 85 filaments stack of an 85x7

Table 1. Details of the wires studied.

Architecture	37×18 (std wire)	27×7 (sparse filament)	55×18 (std wire)
Number of filaments	666	189	990
Nominal as-drawn filament diameter (μm)	14.9	16.8	11.6
Nominal bundle diameter (μm)	120	200	130
Billet number	PMM100712 PMM130723-2	PMM080404-2	PMM180627
Powder source	Nexans	Nexans	Engi-Mat
J_c(5 T, 4.2 K) (A mm^{-2})	3200	2700	5330
Fill factor	0.237	0.081	0.227

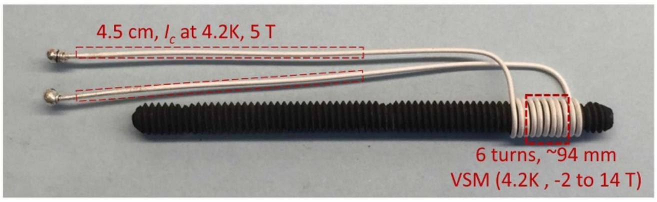

Figure 2. A straight, 0.8 mm diameter Bi-2212 RW wound onto an ITER standard screw with a 5 mm groove diameter and 1 mm groove separation. The samples were heat treated on the Inconel 600 screw, after which a 6 turn coil section and two 4.5 cm straight sections were extracted.

wire with solid Ag rods, to increase the Bi-2212 inter-filament separation [16].

2.2. Sample preparation and measurement details

Coils were prepared for hysteretic loss measurements and analyzed according to the ITER standard AC loss measurement procedure [17]. Approximately 30 cm long unprocessed wire segments were twisted using a custom-made rig. After twisting to the desired twist pitch, the wire was wound onto an Inconel 600 screw with a 5 mm groove diameter and 1 mm groove separation (figure 2). Two straight sections were left at each end for later transport measurements. For reference, each sample set included wires that were not-twisted, which are taken to have a twist pitch of L_p equal to the total coil sample length (∼94.25 mm).

The samples were heat treated on the Inconel screw, under 50 bar in an Ar–O_2 mixture with a pO_2 = 1 bar, using the OP technique which significantly increases J_c by maximizing the filament density [1]. The wire diameter shrank to ∼0.78 mm for all wires. After the heat treatment, 4.5 cm segments were cut from the straight sections for transport measurements and a 94 mm long, 6-turn coil was cut for magnetization measurements. Single sample sets of not-bridged 27×7 and partially bridged 55×18 wires were prepared, while 3 partially bridged 37×18 wire sets were prepared and measured.

The filament diameters and Bi-2212 cross section areas were measured on fully densified samples heated to 820 °C under isostatic pressure of 50 bar with 1 bar O_2 without melting the Bi-2212. This densification aided image analysis and shrank the as-drawn 0.8 mm wire diameter to ∼0.78 mm for all wires. Scanning electron microscope (SEM) micrographs of the fully-processed Ag–Mg alloy sheathed, 0.8 mm diameter, pure Ag matrix Bi-2212 RWs used in the study are shown in figure 1.

Standard 4-point transport measurements were performed in a 15 T Oxford magnet at 4.2 K and 5 T field perpendicular to the wire axis. Wire I_c values were calculated using a voltage criterion of 1 μV cm^{-1} and J_c (4.2 K, 5 T) values were derived using the expression $J_c = I_c/A_{2212}$, where A_{2212} is the area of the superconducting cross section of fully densified unreacted wires measured using digital light microscopy. As noted in a recent study, the J_c (H) characteristics of Bi-2212 are very uniform, making the extrapolation to other field values simple [18]. Magnetization loops were measured in a 14 T Oxford Vibrating Sample Magnetometer at 4.2 K, with the field applied parallel to the coil axis that was continuously swept between −2 T and 14 T at a rate of 0.6 T per minute. The hysteretic losses were calculated by integrating the area inside the magnetization loop from −3 T to 3 T (±3 T loop).

Effective filament diameter values were calculated using the standard equation:

$$d_{eff} = \frac{3\pi}{4}\frac{\Delta M(5T)}{J_c(5T)} = \frac{3\pi}{4}\frac{\Delta m(5T)}{L \cdot I_c(5T)}, \quad (1)$$

derived from the critical state model formula for the magnetization of a cylindrical superconductor in a field applied transverse to the cylindrical axis. ΔM is the difference in magnetic moment between the paramagnetic and the diamagnetic envelopes (Δm) normalized to the sample superconducting volume, and L is the length of a coil sample (94.25 mm). The d_{eff} defined by the formula is proportional to the transport J_c normalized sample magnetization, and more specifically is the diameter of a single cylindrical superconductor with a transport J_c and magnetization equivalent to that of the measured sample. We note here that the electronic and grain-growth anisotropy of the Bi-2212 grains and filaments departs significantly from the cylindrical geometry assumed in equation (1). Indeed there is no simple expression with which to accurately describe the filament shapes and we always found that the calculated d_{eff} was greater than the RW diameter of the filaments established by the densification heat treatment before reaction.

3. Results

Shen *et al* described two filament bridge types found in partial melt-processed high J_c Bi-2212 RWs [11]. Type-A bridges are 3-5 μm thick colonies of Bi-2212 grains that span the entire cross-sectional width of two or more filaments, thus bonding multiple filaments together with continuous colonies of Bi-2212 grains, which are assumed to be a path of high-J_c inter-filament current. In contrast, Type-B bridges are typically less than 2 μm thick Bi-2212 outgrowths that randomly impinge upon a neighboring filament and thus are mostly high angle grain boundaries. Although the specific behaviors of Type A and B bridges are not certain, our view is that Type-B bridges do not constitute high-J_c paths, since they are thinner and narrower than Type-A connections and generally connected only by high-angle grain boundaries that are likely to be weakly linked [11]. Figure 1 shows examples of Type-A and Type-B bridges marked red and blue, respectively.

Figures 1(a), (c) and (e) show that all 3 types of wire lack observable bridging between bundles. However, magnified views of the sub-bundles in the 37×18 wire (figure 1(b)) as well as the 55×18 wire (figure 1(f)) reveal significant Type-A bridging (marked red in the figures). In some cases, 2 or more filaments essentially merged into a single filament. We do note that there was a smaller fraction of merged filaments in the 55×18 wire than the 37×18. In marked contrast, the 27×7 wire is virtually free of Type-A bridging as can be seen in figure 1(d) and more clearly in figure 1(c), with only rare outgrowths establishing Type-B connections (marked blue in the figure). Due to the expected high-J_c capacity of Type-A bridges explained above, for the remainder of this text we will refer to densely packed wires and sparsely packed wires as 'partially bridged' and 'not-bridged', respectively.

Magnetization loops measured at 4.2 K for selected wires with and without twisting are presented in figure 3. All loops were symmetric and flux-jump free, indicative of stable and well-connected behavior, as is typical of Bi-2212 RWs. As expected, twisting reduced the magnetization. The reduction due to twisting is smaller for the partially bridged (55×18 and 37×18) wires (figure 3(a)) than for the not-bridged 27×7 wires (figure 3(b)). Twisting to $L_p = 12$ mm reduced peak magnetization in the 55×18 and 37×18 wires by ∼25% and 15%, respectively. In contrast, reduction due to twisting was 60% in the not-bridged 27×7 wire. The superconductor volume normalized zero field magnetizations were systematically different. The highest J_c 55×18 wire had about twice the peak magnetization of the lower J_c 27×7 wire and also twice the J_c (figure 4).

Figure 4 shows the transport J_c (4.2 K, 5 T) curves of all samples as a function of twist pitch L_p, where the effective L_p for the not-twisted wires is the coil length (94 mm). The principal result is that J_c is independent of L_p except for fluctuations around a constant mean J_c. Even the smallest twist pitch (12 mm) does not lower transport J_c. The 55×18 wire has the highest mean J_c (5 T) ∼5330 A mm^{-2}, which is almost 70% higher than that of the 37×18 wires (∼3200 A mm^{-2}), which is 18% higher than the 27×7 wire (∼2700 A mm^{-2}). The three sets of 37×18 wires had very similar J_c values at all twist pitches, except for one $L_p = 40$ mm 37×18 wire whose J_c was ∼500 A mm^{-2} less than the mean for the other two 37×18 wires for reasons that are unclear.

Figure 5(a) plots AC losses per cycle normalized to the total volume of the wire (Q_{wire}) as a function of twist pitch L_p. Twisting reduced Q_{wire} monotonically in both partially bridged and not-bridged wires, with the loss plateauing at L_p smaller than 25 mm for the 37×18 and 27×7 wires. Twisting reduced Q_{wire} by a maximum of ∼200 kJ m^{-3} in the 55×18 wire, by a maximum of ∼155 kJ m^{-3} in 37×18 wires, and by a maximum of ∼55 kJ m^{-3} in the 27×7 wire. Q_{wire} losses for the 55×18 wires were on average ∼170 kJ m^{-3} higher than Q_{wire} for the 37×18 wires. In contrast, the losses in the 37×18 wires were significantly higher, ∼400 kJ m^{-3}, at all twist pitches, compared to the 27×7 wire. Despite losses for the 37×18 wires being 400 kJ m^{-3} higher than for 27×7 wire, the losses for the 37×18 wires with $L_p \leqslant 40$ mm were slightly lower than the 500 kJ m^{-3} maximum specified loss in ITER Nb_3Sn strands [17]. The 55×18 wire had a minimum loss only ∼90 kJ m^{-3} higher than the ITER specification, even though J_c in the 55×18 wire is 2/3 higher than in Nb_3Sn. For the 37×18 wires, Q_{wire} values were consistent over the three sample sets, except for the single $L_p = 40$ mm wire with reduced J_c, which had a Q_{wire} value ∼40 kJ m^{-3} higher than that of the other two $L_p = 40$ mm 37×18 wires.

The drastic difference in loss reduction between partially bridged and not-bridged wires is shown clearly in figure 5(b), which plots hysteretic losses per cycle normalized to the superconducting volume (Q_{sc}) as a function of twist pitch. Comparing wires twisted to $L_p = 12$ mm to not-twisted wires, the losses dropped by ∼70% in the not-bridged 27×7 wire and by a more modest ∼30% and ∼34% in partially bridged 37×18 and the higher J_c 55×18 wires, respectively. The minimum Q_{sc} for 37×18 wires was only 6% higher than that of the not-twisted 27×7 wire, despite the ∼300% difference between their Q_{wire} values.

While figure 5 shows that the partially bridged and not-bridged wires are clearly different, the nature of the differences are revealed better in figure 6, which shows total losses Q_{sc} of both not-twisted and 12 mm twist pitch wires as a function of field ramp rate $\dot{H}$ normalized to their respective minimum values. Both the partially bridged and the not-bridged twisted wires exhibited an approximately logarithmic dependence of the loss on ramp rate. The not-twisted wires show that losses for the partially bridged 37×18 wire also increased logarithmically with increasing field ramp rate, while losses for the not-bridged 27×7 wire increased nearly linearly with increasing ramp rate. While hysteretic losses due to currents flowing in the superconducting filaments are ideally independent of $\dot{H}$ when screening currents are confined to each independent superconducting filament, it was earlier reported that Bi-2212 losses are moderated by flux creep, and scaled logarithmically with ramp rate [9]. On the other hand, the eddy-current coupling losses across the Ag matrix should scale linearly with ramp rate $\dot{H}$ [5], which is indeed what occurs in the not-twisted, not-bridged 27×7. The not-bridged but twisted 27×7 wire samples displayed a logarithmic dependence of the loss on ramp rate, indicating that eddy current

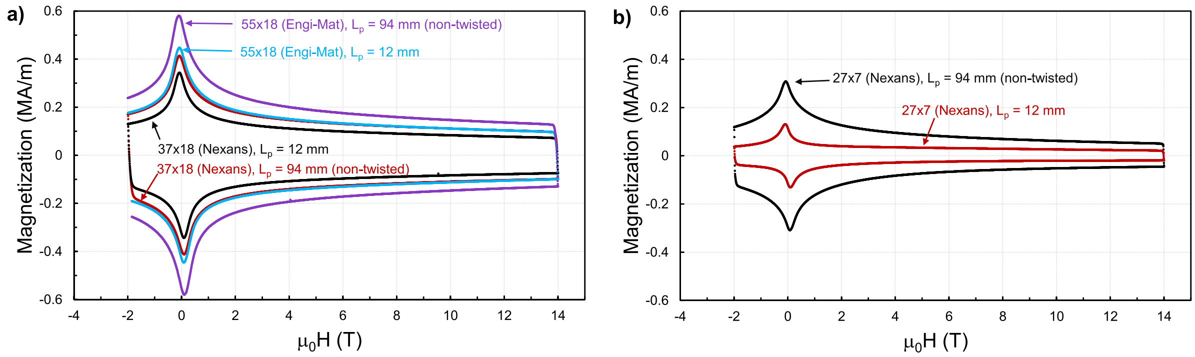

Figure 3. Magnetization loops, normalized to superconductor volume, of (a) densely packed, partially-bridged 37 × 18 wires, (b) sparsely packed, not-bridged 27 × 7 wires. In each case 94 mm long, not-twisted wires are compared to the same wires with a 12 mm twist pitch.

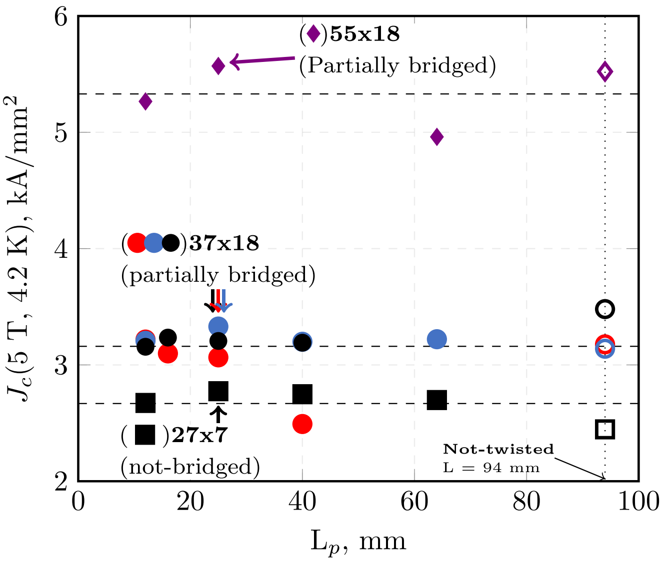

Figure 4. Transport J_c (4.2 K, 5 T) with the field applied perpendicular to the wire axis, as a function of twist pitch (L_p). The horizontal dashed lines show the respective mean values for each sample set. The vertical dashed line marks the 94 mm length of the not-twisted wires represented by hollow samples.

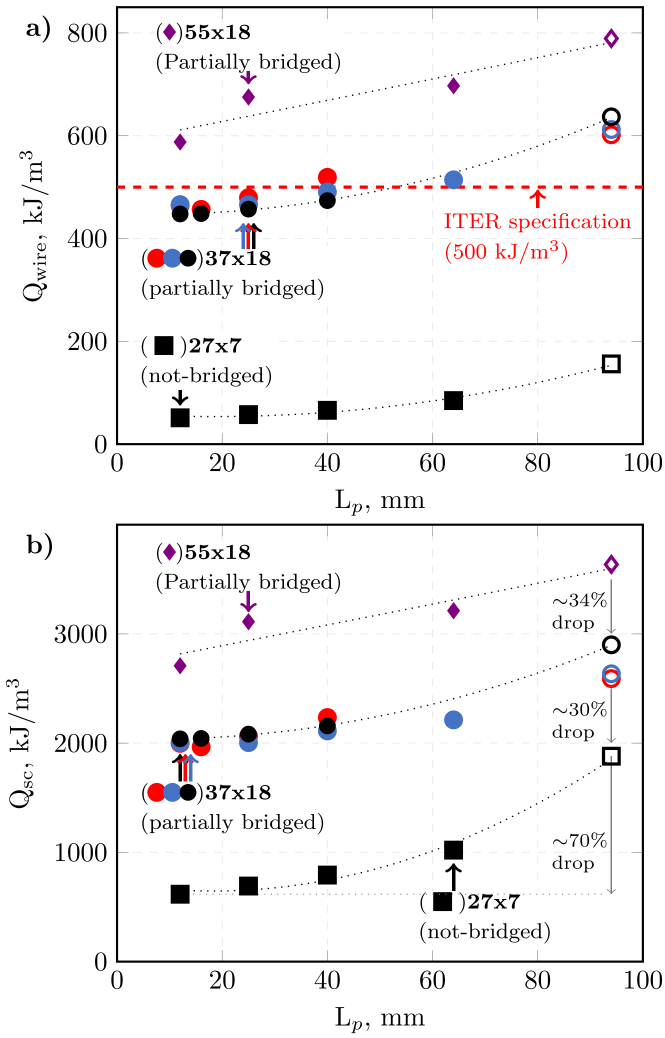

Figure 5. Hysteretic loss per cycle as a function of twist pitch (L_p) normalized to wire volume (a), and Bi-2212 volume (b). The red horizontal dashed line marks the 500 kJ m^{-3} ITER specified loss maximum for Nb_3Sn reference strands. The black dashed lines are guides for the eyes, and the not-twisted samples are represented by hollow markers.

losses are effectively eliminated by twisting which reduce the total loss to the intra-filament hysteretic baseline. By contrast, both the twisted and the not-twisted partially bridged 37 × 18 wires exhibited a logarithmic dependence of loss on field ramp rate, indicating that the dominant loss in these wires is bridging-induced loss. The slope of the not-twisted 37 × 18 wires is noticeably larger compared to the twisted 37 × 18 and 27 × 7 wires, which, when combined with its higher Q_{sc}, indicates that there is some eddy current coupling in the 37 × 18 wire, in addition to the dominant bridging-induced filament coupling.

The effective filament diameter d_{eff} plotted as a function of twist pitch in figure 7 also shows the drastic difference in the degree of inter-filament coupling between partially bridged and not-bridged wires. The not-twisted 55 × 18 and 27 × 7 wires both had the same d_{eff} of ∼150 μm, while the twisted 27 × 7 wires had the lowest d_{eff} of all three types of wire. Moreover, the minimum d_{eff} values for 37 × 18 and 55 × 18 wires were similar to or larger than their respective bundle diameters (see table 1 and figure 7), whereas the minimum d_{eff} for 27 × 7 was ∼25% of the bundle diameter and

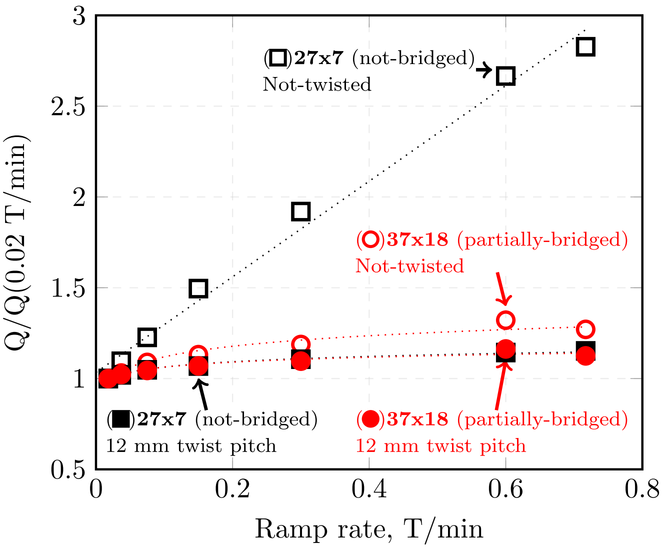

Figure 6. Hysteretic loss values for the two wires made with Nexans powder (27 × 7 and 37 × 18) as a function of field ramp rate. Hollow markers represent not-twisted samples.

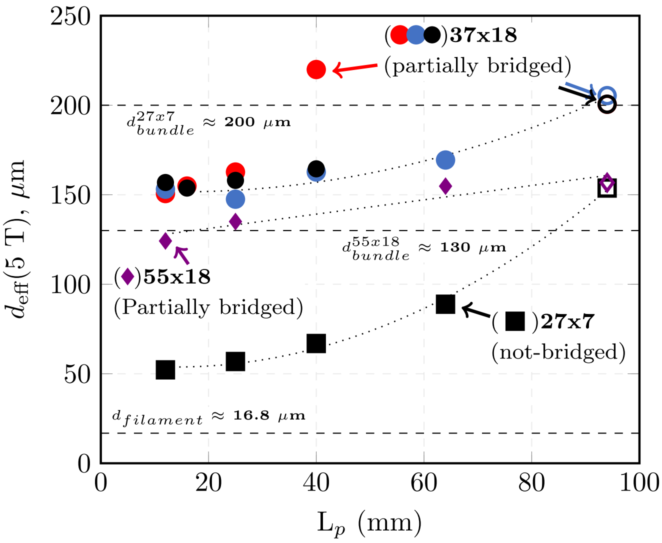

Figure 7. Effective filament diameter (5 T, 0.6 T min^{-1} ramp rate) as a function of twist pitch (L_p). The black dashed lines indicate the filament and bundle diameters for the partially bridged 55 × 18 and the not-bridged 27 × 7 wires. The bundle diameter for the 37 × 18 wire is not indicated, as it is only 10 μm higher than that of the 55 × 18 wire. Hollow markers represent not-twisted samples.

only 35 μm higher than the as-drawn (round) filament diameter. The results for our partially-bridged wires are consistent with reports of $d_{eff} \sim d_{bundle}$ [8] and $d_{eff} > d_{bundle}$ in the literature [14, 15]. The higher J_c 55 × 18 wires had smaller d_{eff} than the 37 × 18 wires at every twist pitch, despite the 55 × 18 wire having 70% higher J_c. In contrast, unlike with the 37 × 18 wires, the minimum d_{eff} in the 55 × 18 wire was approximately equal to the bundle diameter. Unsurprisingly, the $L_p = 40$ mm 37 × 18 wire with low J_c and high loss values had a higher d_{eff} compared to the other two 37 × 18 wires. The not-twisted, not-bridged 27 × 7 wire had a maximum d_{eff} value of ∼150 μm, which is almost identical to the minimum value for the twisted 37 × 18 wire, whereas d_{eff} for the 27 × 7 wire dropped to a minimum of 52 μm in the twisted state.

4. Discussion

The aim of our experiment was to explore hysteretic losses as a function of twist pitch in three significantly different architectures of high J_c OP Bi-2212 RWs, and to determine (a) the lowest Bi-2212-volume-normalized hysteretic loss without loss of J_c, (b) the extent to which strongly-coupled filament-to-filament bridging contributes to the total losses, and (c) to determine the effectiveness of twisting in reducing the total losses of wires having partially bridged and not-bridged filaments.

Figures 4 and 5 show that twisting OP Bi-2212 RWs to a twist pitch as short as 12 mm reduced hysteretic losses in all wires, without damaging the wires or reducing transport J_c. The minimum Q_{sc} values were ∼2700 kJ m^{-3} for the partially bridged 55 × 18 wire, ∼2000 kJ m^{-3} for the partially bridged 37 × 18 wire, and ∼600 kJ m^{-3} for the not-bridged 27 × 7 wire. Comparing wires twisted to $L_p = 12$ mm to not-twisted wires, hysteretic losses dropped by ∼70% in the not-bridged 27 × 7 wire and by a more modest ∼30% and ∼34% in partially bridged 37 × 18 and the higher J_c 55 × 18 wires, respectively. Thus twisting is clearly a process that benefits all Bi-2212 wires.

Standard Bi-2212 wires with packing factors of ∼20% that generate significant bridging density (37 × 18 and 55 × 18 wires) had significantly higher Q_{wire}, Q_{sc} (figure 5) and d_{eff} (figure 7) values compared to the not-bridged 27 × 7 wires. Moreover, losses in not-twisted 37 × 18 and 55 × 18 wires scale logarithmically with field ramp rate, indicating that the dominant loss in these wires is bridging-induced loss [9]. The not-twisted 27 × 7 wire not only had smaller hysteretic losses (figure 5) than the 37 × 18 and 55 × 18 wires, but also shows a much larger ramp rate dependence (figure 6), consistent with losses dominated by eddy current coupling across the Ag matrix. These findings show that the superconducting coupling between filaments in our partially bridged 37 × 18 and 55 × 18 wires adds considerably to the total loss (figure 5) and prevents some of the reduction in loss normally produced by twisting. Since the critical coupling length is proportional to the resistivity of the matrix [5], bridging can couple more filaments in a sub-bundle than eddy-current coupling can, as evidenced by the significantly higher d_{eff} of our partially bridged samples. Moreover, screening current loops in bridged wires are not limited by the resistivity of the silver matrix as in the case of eddy-current coupling losses. Although bridging significantly enhanced hysteretic losses in our samples, figure 5 also shows that the lowest Q_{wire} losses in partially bridged wires were only a little above or even below ITER's maximum specified losses for Nb_3Sn wires, even though J_c for the Bi-2212 wires in the current study is up to 70% higher than Nb_3Sn RRP wires at 12 T with a much higher irreversibility field. Thus, twisting is still valuable for enabling standard, high J_e, partially bridged Bi-2212

RWs to meet hysteretic loss requirements of high field magnet applications.

A common parameter characterizing AC loss measurements is the effective filament diameter, d_{eff}, but the problem of applying equation (1) to Bi-2212 is that several of its assumptions are violated. First, J_c must be defined by the quotient I_c/A_{2212} but A_{2212} is far from uniform or cylindrical along the wire due to the plate-like grain structure. Second, it seems very likely that many barriers to current flow operate in the filaments as has been explicitly observed by magneto-optical imaging of monofilament Bi-2212 and Bi-2223 wires [19]. Thus, the effective J_c defined by transport across a 1 cm gauge length is certainly an underestimate of the higher I_c regions of the filament, which are rendered invisible by the current limiting obstructions in the transport current path. These higher I_c regions contribute to total hysteretic losses without adding to the long-range transport J_c defined by I_c/A_{2212} but A_{2212}. Indeed, recent measurements of the mean (μ) and standard deviation (σ) of the critical current distribution of I_c values from d^2V/dI^2 measurements [20] show that σ/μ is about twice larger for Bi-2212 than for good Nb-Ti conductors, which in contrast have good I_c uniformity due to their isotropy, their strongly-coupled grain boundaries, and uniform longitudinal cross section. In addition, both the microstructural evidence of figure 1 and the ramp rate evidence from figure 6 demonstrate that superconducting bridging occurs and that it changes the nature of the dominant hysteretic losses in the not-bridged and partially bridged Bi-2212 wire architectures studied here. Finally, we note two additional factors that enhance d_{eff}: the first being that the filament shape is far from cylindrical for all three architectures in figure 1, particularly for the partially-bridged wires; the second is that the Bi-2212 grains have a strong electromagnetic anisotropy of order 30, meaning that grains having their *c*-axes far from the local magnetic field vector will have much higher J_c than those where H is close to parallel to the *c*-axis.

Given these uncertainties, it is instructive to compare the calculated d_{eff} for the most heavily twisted 27×7 wire, where filament-to-filament bridges do not amplify the loss, to the as-drawn $d_{filament}$ which is 16.8 μm (table 1). The calculation of d_{eff} that ignores all the complications discussed above yields a filament diameter of 52 μm, some 3.1 times bigger than the round-wire $d_{filament}$ deduced before reaction to the anisotropic grain state.

Turning to the partially bridged wires, we see that, despite having higher total losses, the 55×18 wire had a lower d_{eff} compared to the 37×18 wire at all twist pitches. A recent comparison of I_c distributions in older Nexans-powder 37×18 and more modern Engi-Mat 55×18 wires showed that the distributions were substantially narrower in the higher J_c 55×18 wires, which is suggestive of better current-path connectivity compared to the 37×18 wires [3, 20]. Other contributing factors are the reduction in filament bridging in the Engi-Mat wire that resulted from the re-optimization of the heat treatment for this new powder and architecture, and also its $\sim$3 μm smaller filament diameter compared to the Nexans 37×18 wire [3]. A higher intra-filament hysteretic loss for the 55×18 wire follows from its substantially higher J_c, but its substantially smaller filament bridging reduces the filament-to-filament coupling component of the loss. These results indicate that even in the partially bridged, not-twisted state, high J_c OP Bi-2212 RWs have hysteretic losses comparable to LTS conductors, and that it may be possible to drive losses down even closer to the uncoupled hysteretic baseline in the twisted state by optimizing the heat treatment and filament separation to reduce filament bridging. That Bi-2212 RW losses can be reduced to LTS level losses is very significant, especially given that the whole wire current density J_e(4.2 K, 12 T) $\approx$ 1200 A mm^{-2} of the state-of-the-art 55×18 Bi-2212 RWs made with Engi-Mat powder that were used in this study is about twice the J_e(4.2 K, 12 T) $\approx$ 600 A mm^{-2} of the Nb_3Sn reference strands characterized in Seiler *et al*'s study [17].

5. Conclusion

We found that twisting did not decrease J_c, but also that it reduced the volumetric hysteretic losses by 30%–35% in partially bridged OP high J_c Bi-2212 RWs, and by a much more significant 70% in not-bridged wires having discrete filaments. Moreover, filaments in the twisted, not-bridged wires were completely decoupled, whereas the twisted, partially bridged wires exhibited losses normalized to the superconducting volume that were similar to the not-twisted, not-bridged wire. Remarkably, twisting reduced the wire-volume-normalized losses in previous generation partially bridged wires made with Nexans powder to losses slightly below the ITER specified maximum loss of 500 kJ m^{-3}. State-of-the-art twisted Bi-2212 RWs made with the new higher J_c Engi-Mat powder exhibited only $\sim$34% higher minimum losses per superconducting volume than previous generation wires made with Nexans powder, despite having 70% higher transport J_c. This significant improvement in transport J_c normalized hysteretic loss (d_{eff}) is due to a reduction in filament bridging that resulted from the re-optimization of the heat treatment to the new powder and architecture, indicating that future wires might achieve even lower losses if filament separation and heat treatment parameters are optimized. These results highlight Bi-2212's significance as the only high field, high J_c, low hysteretic loss HTS wire, and its utility for ultra-high field, low-hysteretic-loss, high-field-quality applications.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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