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ORIGINAL ARTICLE

Improved trapped field performance of single grain Y-Ba-Cu-O bulk superconductors containing artificial holes

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Abstract

The intrinsic mechanical properties of single-grain RE-Ba-Cu-O bulk high-temperature superconductors can be improved by employing a thin-wall geometry. This is where the samples are melt-processed with a predefined network of artificial holes to decrease the effective wall thickness. In this study, the tensile strengths of thin-wall YBCO disks were determined using the Brazilian test at room temperature. Compared with conventional single grain YBCO disks, the thin-wall YBCO disks displayed an average tensile strength that is 93% higher when the holes were filled with Stycast epoxy resin. This implies a thin-wall sample should, in theory, be able to sustain a trapped field that is 39% higher without exceeding the mechanical limit of the sample. High-field magnetization experiments were performed by applying magnetization fields of up to 11.5 T, specifically to break the samples in order to verify the effect of increased mechanical strength (and improved cooling) on the ability of bulk (RE)BCO to trap field successfully. The standard YBCO sample failed when it was magnetized with a field of 10 T at 35 K, suffering permanent damage. As a result, the standard sample could only trap a maximum surface field of 7.6 T without failure. On the other hand, the thin-wall YBCO sample survived all magnetization cycles, including a maximum magnetization field of 11.5 T at 35 K, demonstrating a greater intrinsic ability to withstand significantly higher electromagnetic stresses. By subsequently field-cooling the thin-wall sample with 11 T at 30 K, a surface field of 8.8 T was trapped successfully without requiring any external ring reinforcement.

KEYWORDS

brittle materials, magnetic materials/properties, mechanical properties, superconductors, yttrium/yttrium compounds

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1 | INTRODUCTION

The high-field performance of single grain RE-Ba-Cu-O [or (RE)BCO, where RE = Y or a rare earth element] bulk high-temperature superconductors is limited by a combination of their mechanical and thermal properties, in particular, their mechanical strength and thermal conductivity.[1] At present, low values of these parameters lead to brittle failure and flux jumps, respectively, during high-field magnetization processes.

Trapped fields over 17 T have been achieved in single grain (RE)BCO bulk superconductors as a result of improvements made to their mechanical and thermal properties via various post-melt-processing treatments. Tomita and Murakami achieved a trapped field of 17.24 T at 29 K in 2003 in a stack of two 26.5 mm diameter YBCO samples reinforced with resin and alloy impregnation along with carbon fiber wrapping.[1] In 2014, Durrell et al. exceeded this performance by demonstrating a trapped field of 17.6 T at 26 K in a stack of two 24 mm diameter Ag-doped GdBCO bulk superconductors reinforced with shrink-fit stainless-steel rings.[2] More recently, Huang et al. measured trapped fields of 16.8 and 17.6 T, at 26 and 22.5 K, respectively, in a stack of 24 mm diameter GdBCO/Ag reinforced with stainless steel laminations and shrink fitted with stainless-steel rings to demonstrate improved reliability of these technologically important materials.[3]

A magnetic field exceeding 17 T is an order of magnitude stronger than the maximum fields that can be reached with conventional permanent magnets. The remarkable properties of (RE)BCO bulk superconductors as compact and standalone sources of a high magnetic field, therefore, have tremendous potential for a range of sustainable engineering applications, including ultra-light superconducting rotating machines, desktop MRI/NMR systems, and magnetically targeted drug delivery.[4]

In addition to the post-melt-processing treatments described above, modifications can be made prior to melt processing to improve the microstructure and intrinsic properties of single grain (RE)BCO bulk superconductors. For example, significant porosity is often observed in large single grains as a result of pockets of residual inert gas and oxygen gas, originating during peritectic decomposition, that become trapped in the viscous melt during solidification.[5,6] Porosity in the sample microstructure is clearly undesirable due to the detrimental effect it has on the mechanical[7] and superconducting properties of (RE) BCO bulk samples.

An established technique to address the issue of high porosity is to fabricate single grains containing an array of artificial columnar holes patterned into the pellets of pressed precursor powder.[5,8–12] This is sometimes referred to as the "thin-wall" geometry. The artificial holes, typically each around 1 mm in diameter, then provide shortened paths for gas to escape from the sample microstructure during melt processing, resulting in reduced porosity within the superconducting matrix. In addition to reduced porosity, the benefits associated with the thin-wall geometry also include, first, an increase in the specific surface area of the samples, which allows for more homogeneous and improved cooling that can be useful in preventing flux jumps[1,13]; second, a decrease in the effective wall thickness, which assists with a more rapid and homogeneous oxygenation of the samples; and third, bulk microstructure almost free of oxygenation cracks along the *ab*-planes have been reported in thin-wall YBCO when processing was coupled with progressive oxygenation.[14]

Melt processing bulk samples with artificial holes is a straightforward technique to implement, since it requires only one step to be added to the standard top-seeded melt growth (TSMG) fabrication process, namely the patterning of the artificial holes in the green body preform. Furthermore, it has been shown that samples grown with artificial holes do not suffer degradation in superconducting properties. On the contrary, some perforated single grain samples have exhibited higher trapped magnetic fields than hole-free samples.[12]

YBCO single grains processed with artificial holes have attracted attention recently from commercial suppliers of (RE)BCO bulk superconductors.[15,16] These samples were considered for superconducting bearing applications, in particular, where the use of bulk single grains enables high efficiency and reduces significantly contact, wear, and frictional losses.

In this study, the tensile strength of thin-wall single grain YBCO samples was characterized using the Brazilian test (a technique used commonly for determining the tensile strength of cylindrical specimens of brittle materials[17,18]) and compared to standard YBCO samples grown under similar conditions. To confirm that mechanical strength has an impact on trapped field performance, each sample was subjected to successive field cooled magnetization at 35 K with an increasing magnetization field of up to 11.5 T. The aim of this was to deliberately fracture the single grain samples under the Lorentz force and to determine whether the thin-wall YBCO could survive more extreme field conditions due to its potentially improved mechanical strength. The proposed study is similar in nature to that of Fuchs et al., where it was deduced the tensile strength of bulk YBCO is approximately 25 MPa based on the field at which the sample failed.[19] This provides important insight into the applied properties of single grain (RE)BCO bulk superconductors, since most methods of determining the strength of these materials involve mechanical tests on small, un-magnetized specimens extracted from a large single grain, for example, via the three-point bend test or the Vickers hardness test. By magnetizing the as-manufactured single grains until failure, we can establish directly the limitations of these materials for potential application as trapped field magnets. In addition, a study combining both mechanical and magnetization tests on a batch of nominally identical samples could also help to assess the accuracy of the mechanical testing technique employed for their characterization.

2 | EXPERIMENTAL DETAILS

2.1 | Sample fabrication

The single grain YBCO samples used in this study were fabricated by CAN SUPERCONDUCTORS using the fabrication procedure described in detail in Ref. [20]. In summary, precursor powder with stoichiometric composition of $Y_{1.8}Ba_{2.4}Cu_{3.4}O_x$ + 0.5 wt% CeO_2 was pressed uniaxially into pellets with a predefined network of columnar holes of 1.1 mm diameter using a "spiked die" as shown in Figure 1A.

The pellets were then processed via top-seeded melt growth (TSMG) in air under isothermal conditions with commercial thin films of Nd-123 on MgO (2 mm × 2 mm) as seed crystals to produce YBCO single grains. To facilitate the tetragonal (non-superconducting) to orthorhombic (superconducting) transition, the samples were annealed in flowing oxygen between 300 and 450°C for 150 h. Finally, all YBCO disks were machined to a diameter of 27 mm and thickness of 10 mm for characterization.

A reference batch of standard YBCO disks fabricated without artificial holes was also prepared under the same conditions to enable a meaningful comparison of the properties of the samples containing artificial holes.

2.2 | Mechanical and microstructural characterization

The Brazilian test was chosen to determine the tensile strength of the YBCO single grains.[21] The benefits of utilizing the Brazilian test for this study include, first, the cylindrical geometry of Brazilian test specimens means minimal sample preparation is required, which, in turn, minimizes the introduction of defects during cutting and polishing. Second, a strength value representative of the whole bulk superconductor can be acquired, which would ideally correlate more closely with the field at which mechanical failure is expected during high-field magnetization. On the other hand, data from a three-point bend test or tensile test may overestimate strength due to the small specimen volume used. A consequence of Weibull statistics is that two brittle samples with identical defect distributions but of different sizes will possess different failure strengths[22]; that is, the smaller sample will have a higher mean strength. Third, the bulk-to-bulk variation in strength can also be determined using the Brazilian test on a batch of single grain samples fabricated nominally identically, indicating any scatter in mechanical strength, which may be important in realizing practical applications of single grain (RE)BCO.

For the Brazilian test, the thin-wall YBCO single grains were compressed along their growth sector boundaries using aligned steel platens, following the orientation used in[21] and as shown in Figure 2A. The compressive load generates a compression-induced tensile stress in the direction perpendicular to that of the applied load. The crosshead speed was fixed at 0.03 mm/min in these tests. The tensile strength was determined from the failure load via Equation (1), where σ is the indirect tensile strength, P

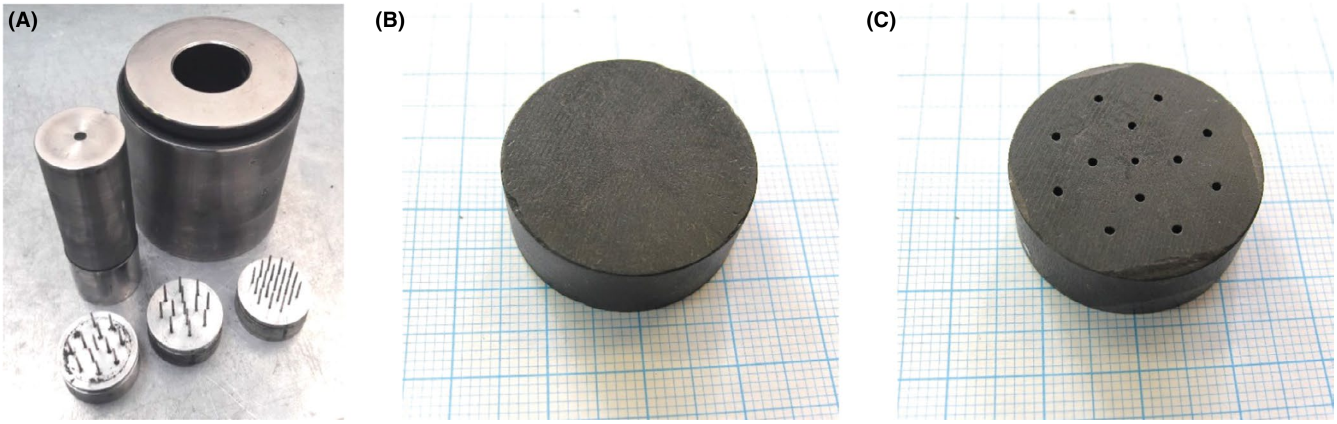

FIGURE 1 (A) A die and spiked punches (with different needle patterns) used to produce columnar holes in pellets of pressed YBCO precursor powder.[29] (B) A standard single grain YBCO disk 27 mm in diameter. (C) A thin-wall single grain YBCO disk 27 mm in diameter. Small columnar holes approximately 1 mm in diameter are visible on the top surface of the superconductor in (C). The samples were manufactured by CAN SUPERCONDUCTORS

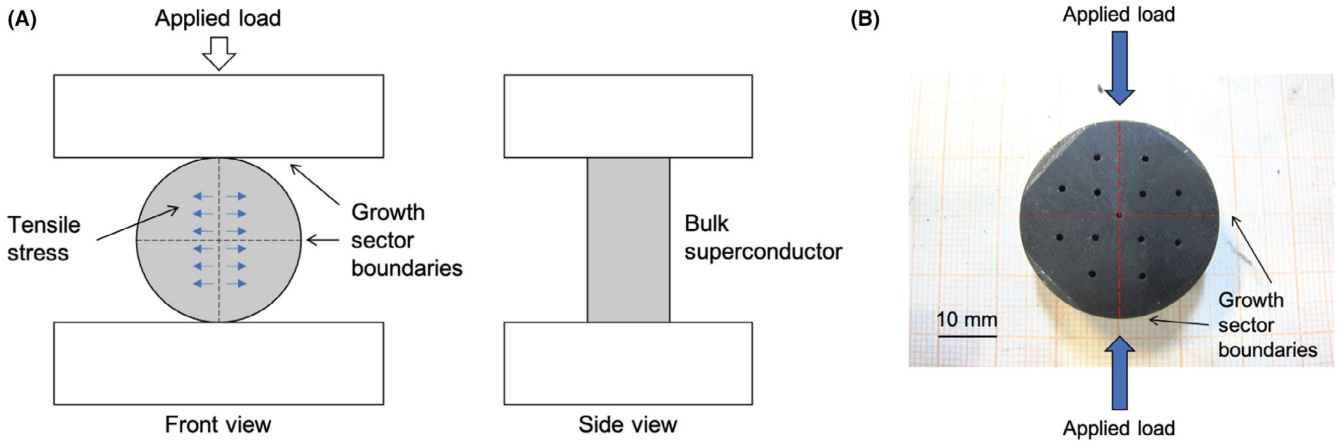

FIGURE 2 (A) Schematic illustration of the Brazilian test arrangement, illustrating the induced tensile stress in the sample. (B) Direction of the applied compressive load on a thin-wall YBCO sample with respect to its growth sector boundaries

is the load at failure, and *D* and *t* are the sample diameter and thickness, respectively.

$$\sigma = \frac{2P}{\pi D t}. \quad (1)$$

Optical micrographs were taken along the cross section of a typical thin-wall sample at half-height to determine the influence of the artificial holes on the sample porosity. *ImageJ* image processing software was used subsequently to quantify the porosity as a fraction of cross-sectional area.[23,24] This procedure was then repeated for standard single grain YBCO samples of the same diameter and thickness.

2.3 | High-field magnetization

The samples were magnetized by field cooling in a 12 T superconducting magnet to attempt to fracture the samples under high field. The samples were fitted loosely in a copper sample holder using Apiezon N vacuum grease to ensure good thermal contact to the holder, Cernox® sensor, and heater, but with minimal mechanical reinforcement, as shown in Figure 3A.

The field cooling procedure consisted of applying an external magnetic field of between 7 and 11.5 T to the sample with the sample temperature maintained at 100 K. The sample was cooled to the measurement temperature of 35 K once the field was reached. The external field was then removed slowly at a rate of 0.04–0.18 T/min when the temperature had stabilized (0.180 T/min from 0 to 4.3 T, 0.128 T/min from 4.3 to 8.6 T, 0.077 T/min from 8.6 to 11.1 T, and 0.040 T/min from 11.1 to 11.5 T due to the magnet limits), as shown in Figure 3B, to establish a trapped field in the sample. The sample was then demagnetized by warming it above its superconducting transition temperature before the next magnetization cycle and set of measurements. The magnetization process was repeated with increasingly higher fields to determine the point at which the electromagnetic stresses due to the Lorentz force exceeded the tensile strength of the superconductor sample.

A linear array of Hall sensors (Lakeshore HGT-2101) was placed on the surface of the sample to measure the field continuously at multiple points along the sample diameter as the external field was ramped down, as shown in Figure 3A.

The magnetization experiments described above were carried out for a typical thin-wall YBCO and typical standard YBCO single grain sample to form a comparison. The quality of the single grain samples (27 mm in diameter) was first confirmed using trapped field measurements at 77 K, where the field profiles showed a sharp conical profile and a high peak value, indicating supercurrents flowing uniformly over the entirety of each sample. The thin-wall and standard samples exhibited similar peak trapped fields of 0.84 and 0.81 T, respectively.

3 | RESULTS AND DISCUSSION

3.1 | Tensile strength of thin-wall YBCO

Figure 4 shows the room temperature tensile strengths σ measured indirectly for the different types of YBCO single grain samples. In total, 12 standard and 16 thin-wall YBCO samples were measured as part of this study. Eight of the thin-wall samples were measured with their holes open,

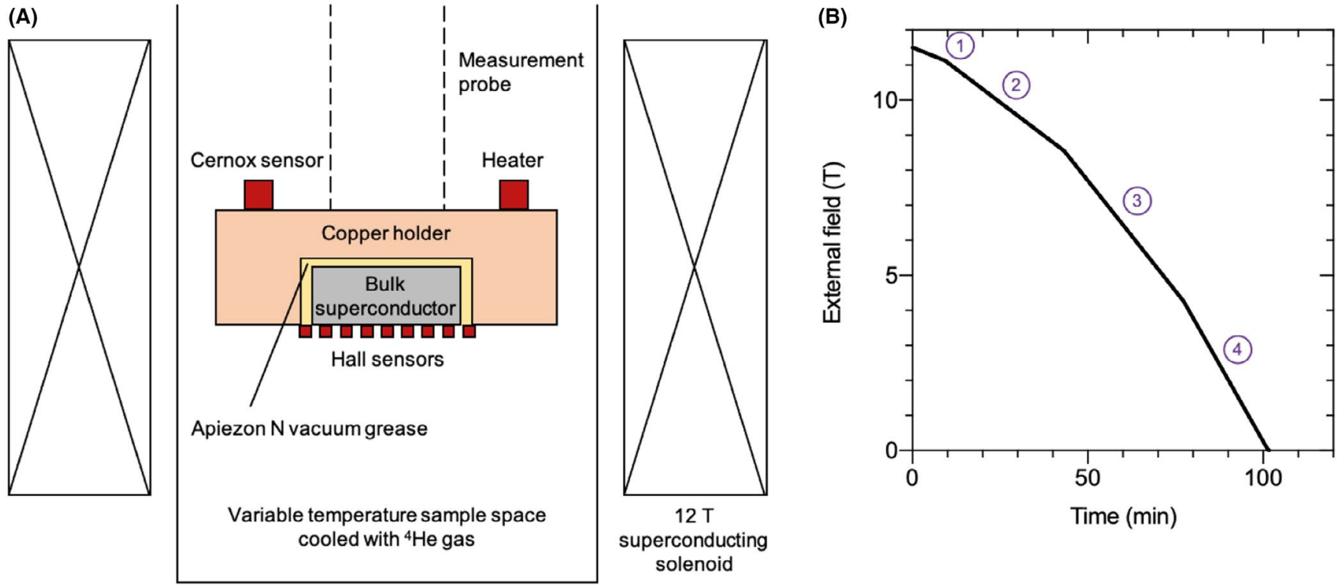

FIGURE 3 (A) Schematic illustration of the magnetization arrangement used in the present study. (B) Ramp rates used for the different field ranges: 1. 0.040 T/min. 2. 0.077 T/min. 3. 0.128 T/min. 4. 0.180 T/min. The rates were set based on the limits of the magnetizing magnet and were fixed for each field range, regardless of the starting field

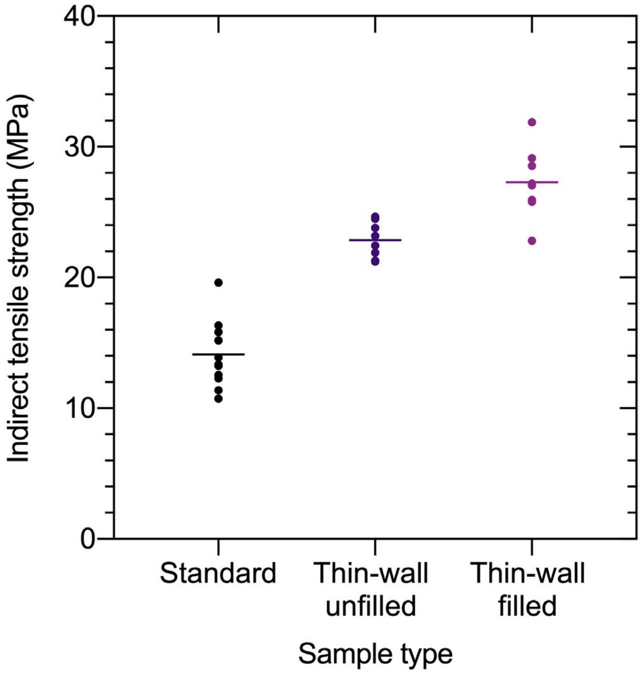

FIGURE 4 Room-temperature tensile strength measured indirectly using the Brazilian test for each type of single grain sample

TABLE 1 Summary of the measured tensile strengths of each type of single grain sample

	Standard	Thin-wall	Filled thin-wall
Average σ (MPa)	14.1	22.9	27.3
Minimum σ (MPa)	10.7	21.2	22.8
Weibull modulus m	6.9	19.1	11.9
Characteristic σ_0 (MPa)	15.1	23.5	28.4
Estimated B_{trapped} permissible by average σ (T)	10.9	13.8	15.1

and eight with their holes filled using Stycast® 2850 FT epoxy resin (mixed with 23 LV catalyst). Stycast has a relatively low Young's modulus (<10 GPa), so the main purpose of resin impregnation was to minimize stress concentration at the artificial holes and to achieve a fair comparison of the strength of the constituent bulk YBCO material. In theory, stiffer and stronger reinforcing materials could have been chosen to further increase the mechanical strength of the filled thin-wall samples, which would then have been better able to resist the Lorentz force during magnetization.

Table 1 shows a summary of the measured tensile strengths of each type of YBCO sample. The average and minimum strengths are shown for each set of results. The average values of σ for the standard YBCO and unfilled thin-wall YBCO samples are 14.1 and 22.9 MPa, representing an improvement of 62%. This demonstrates that, even with the effects of stress concentration, the $YBa_2Cu_3O_{7-\delta}$ (Y-123) bulk superconducting matrix still exhibited considerably better mechanical strength in the thin-wall sample. Furthermore, a clear enhancement in mechanical strength was observed for the case of the thin-wall YBCO filled with Stycast, which yielded an average σ of 27.3 MPa, corresponding to a 93% improvement over the standard samples. These results show that significant enhancements can be made to the mechanical properties of single grain YBCO with the patterning and subsequent filling of artificial holes.

The spread of the strengths for each sample type was then evaluated using Weibull statistics, according to Equation (2). P_{failure} is the cumulative failure probability at a given applied stress σ, m is the Weibull modulus and σ_0 is the characteristic strength (i.e., stress level at which 63.2% of the samples are expected to have failed).

$$P_{\text{failure}}(\sigma) = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right]. \tag{2}$$

The increase in Weibull modulus, from 6.9 for the standard YBCO samples to 11.9 for the filled thin-wall YBCO samples, indicates a narrowing of the distribution of the size of defects, due most likely to the elimination of the largest pores from the microstructure, which is associated with the shortened diffusion paths. This led ultimately to higher and more consistent/reliable failure strengths, which are significant in the development of practical applications of these materials.

Using the Bean model and analytical and numerical solutions for the electromagnetic stresses, we can estimate the maximum field that can be trapped in each sample type before the average tensile strength is exceeded. Tsuchimoto et al. evaluated two-dimensional stress distributions in bulk superconductors using the Bean model,[25] which were solved numerically using a finite difference method. For the aspect ratio used in the present study (height/radius = 10/13.5 = 0.74) these authors estimate the peak hoop stress through the center of the bulk superconductor of finite thickness to be $\sigma \approx 0.3 \times (B_1^2/2\mu_0)$, compared to $\sigma = 0.71 \times (B_1^2/2\mu_0)$ as for the case of an infinitely long, thin superconductor,[26] where B_1 is the trapped field at the center of the latter.

Subsequently, by combining this geometric factor from Tsuchimoto et al. and analytical solutions for partial magnetization by Ren et al.,[26] the magnetic field at which mechanical failure is expected can be estimated from the average tensile strength σ obtained using the Brazilian test. The results are shown in Table 1, where it can be seen the permissible peak trapped field at the center of the bulk superconductor has increased from 10.9 to 15.1 T based solely on the mechanical limits of the samples. The predicted peak trapped field for the standard YBCO disks, calculated based on the measured tensile strength, actually agrees well with the magnetization experiments carried out by Fuchs et al.,[19] where a pair of YBCO disks 24 mm in diameter trapped up to 8.5 T at 51.5 K and failed subsequently.

It is important to note the estimates given in Table 1 are derived from the stress states at the end of the magnetization process and not during the magnetization cycle itself. The electromagnetic stresses experienced during magnetization can exceed the final stress states,[26–28] which is partly why single grain bulk superconductors tend to fail during magnetization rather than afterward. Therefore, the trapped fields calculated in Table 1 should be viewed as slight overestimates based on the tensile strengths obtained.

3.2 | Porosity analysis

Optical micrographs of two sets of typical standard single grain YBCO and thin-wall YBCO, 27 mm in diameter, are shown in Figure 5A, where it is clear that porosity in the bulk microstructure is reduced significantly around the sites of the artificial holes. The results from the analysis of porosity based on these micrographs are shown in Figure 5B, which includes analysis of the two standard samples shown in Figure 5A.

While porosity varies slightly from sample to sample, as evident from the two standard single grain YBCO disks analyzed in Figure 5B, it does appear that the porosity of the thin-wall YBCO sample does not exceed that of the standard YBCO at any position in the sample microstructure and is significantly suppressed around the artificial holes, as anticipated. Therefore, with carefully chosen hole patterns and a sufficiently small hole spacing, the porosity at the center of a thin-wall sample, which is the region that experiences peak tensile stress during magnetization, can potentially be engineered to be relatively low.

3.3 | Trapped field performance of thin-wall YBCO

High-field magnetization was used to attempt to break the samples deliberately to verify the mechanical strengths measured in Section 3.1, where it was shown that the thin-wall single grains were at least 62% stronger than the standard samples. For this, one sample of each type was chosen based on its trapped field performance at 77 K. The standard YBCO and thin-wall YBCO samples exhibited trapped fields of 0.81 and 0.84 T at 77 K. The circumference of each sample was polished to a round geometry to remove any irregularities that may affect the mechanical reliability of the single grain and to ensure a loose fit into the sample holder.

Figure 6A shows the trapped field performance on the surface of the standard single grain YBCO disk with increasing applied field at various temperatures. It is

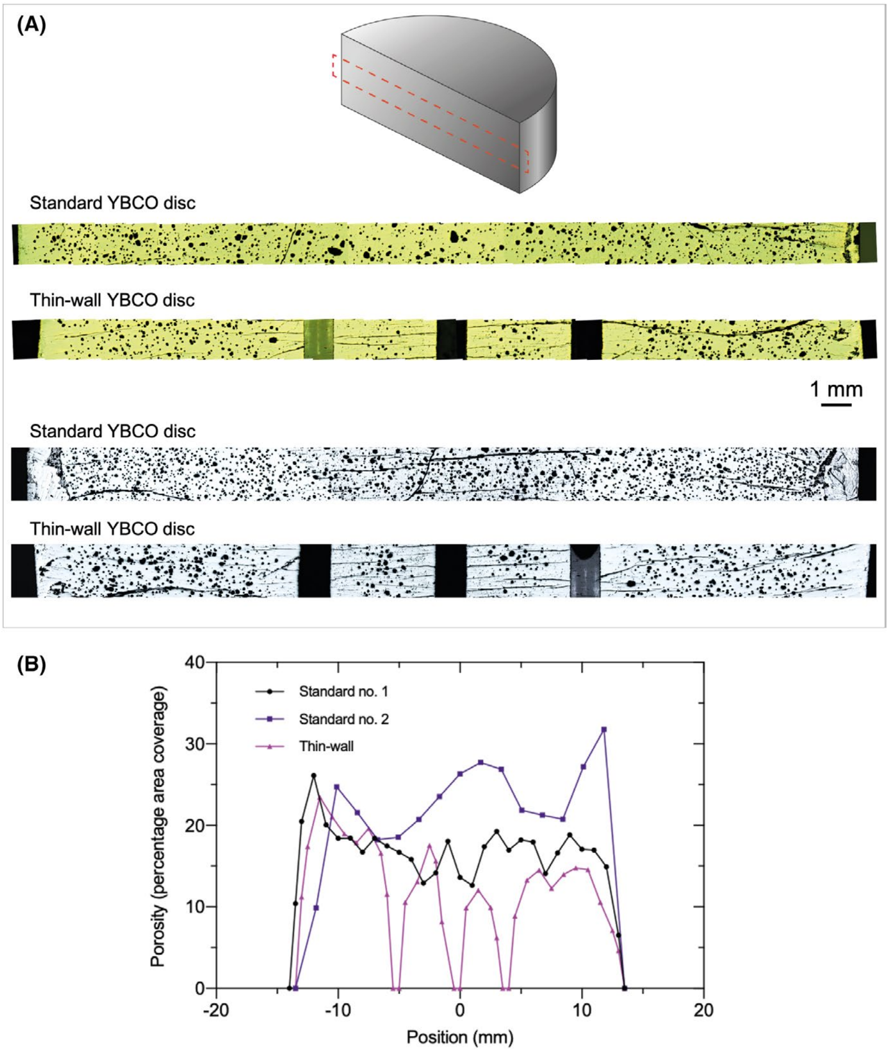

FIGURE 5 (A) Optical micrographs taken across the center of standard YBCO and thin-wall YBCO single grain disks, as illustrated schematically in the top part of the figure. Pores/voids (dark in contrast) are visible in the continuous $YBa_2Cu_3O_{7-\delta}$ (Y-123) bulk superconductor matrix (light in contrast). The three vertical columns at the center of the thin-wall YBCO samples indicate the positions of the artificial holes. (B) Variation of the sample porosity with radial position across each single grain sample

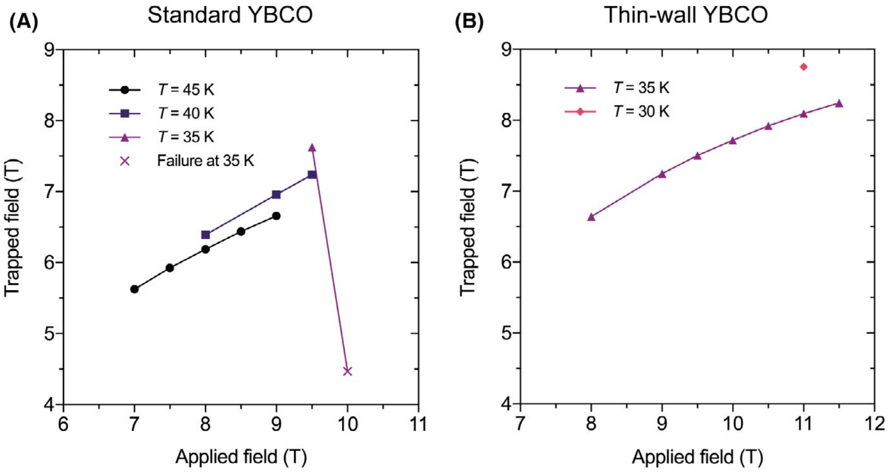

FIGURE 6 (A) Field trapped by the 27 mm diameter standard YBCO sample as a function of applied field and temperature. The sample fractured when it was magnetized with 10 T at 35 K. (B) Field trapped by the 27 mm diameter thin-wall YBCO sample as a function of applied field and temperature. No failure was observed in this sample

important to note the data points correspond to trapped fields measured following complete, independent magnetization cycles; that is, the sample was de-magnetized completely between the recording of each data point. The trapped fields were measured immediately after the complete removal of the external field. Once the sample had survived a cycle, either the applied field was increased, or the target temperature was decreased.

Field cooling of the standard YBCO sample was first carried out at 45 K with an applied field of 7 T. It was then shown that the sample trapped up to 6.66 T at 45 K when the applied field was increased to 9 T. The increase in the trapped field with increasing applied field suggests the sample was not fully magnetized during field cooling, that is, not fully penetrated by magnetic flux.

The target temperature was reduced subsequently to 40 K in order to increase J_c, the trapped field attainable and, most importantly, the electromagnetic stresses within the sample. The standard YBCO trapped up to 7.24 T at 40 K with an applied field of 9.5 T and, again, survived the range of fields applied.

The target temperature was then reduced to 35 K. The standard sample survived the initial magnetization cycle at this temperature with an applied field of 9.5 T and trapped 7.63 T as a result. However, when the applied field was increased to 10 T, the sample suffered either a crack or a flux jump, as indicated by an abrupt decrease in the measured field and a significant rise in sample temperature as the external field was ramped down. Further examination showed the sample had cracked since the trapped field profile at 77 K exhibited significant asymmetry, indicating that it was no longer behaving as a continuous single grain.

The thin-wall YBCO disk was also subjected to field cooled magnetization at 35 K to achieve a fair comparison. The artificial holes were filled with copper wires and solder, as shown in Figure 7A, rather than the Stycast used in samples characterized in Section 3.1, in order to minimize stress concentration but also to assist cooling. This demonstrates the versatility of thin-wall samples and suggests that improvements in the trapped field may be the result of enhancements to both the mechanical and thermal properties of the sample.

The thin-wall sample was field cooled initially with 8 T at 35 K, as shown in Figure 6B, after which the applied field was increased incrementally. A peak trapped field of 7.51 T in the thin-wall YBCO sample, when magnetized with 9.5 T, was similar to that observed for the standard YBCO, which trapped 7.63 T with the same applied field. This suggests the magnetization experiments were a fair comparison and that the electromagnetic stresses generated within the two samples were similar in magnitude.

Figure 6B shows that the thin-wall YBCO sample was able to withstand at least 11.5 T in the applied field (maximum magnetization field attainable with the facilities available) at 35 K, whereas the standard YBCO sample failed at 10 T. This is in agreement with the estimates shown in Table 1.

Finally, field cooling was carried out with 11 T at 30 K to test the thin-wall YBCO single grain even further and to determine the maximum trapped field achievable. Increasing J_c by lowering the temperature should also increase the volume of superconductor under peak tensile stress,[26] making it more susceptible to failure. The thin-wall sample also survived this cycle and trapped a peak surface field of 8.76 T at 30 K immediately after the removal of the external field, as shown in Figure 8.

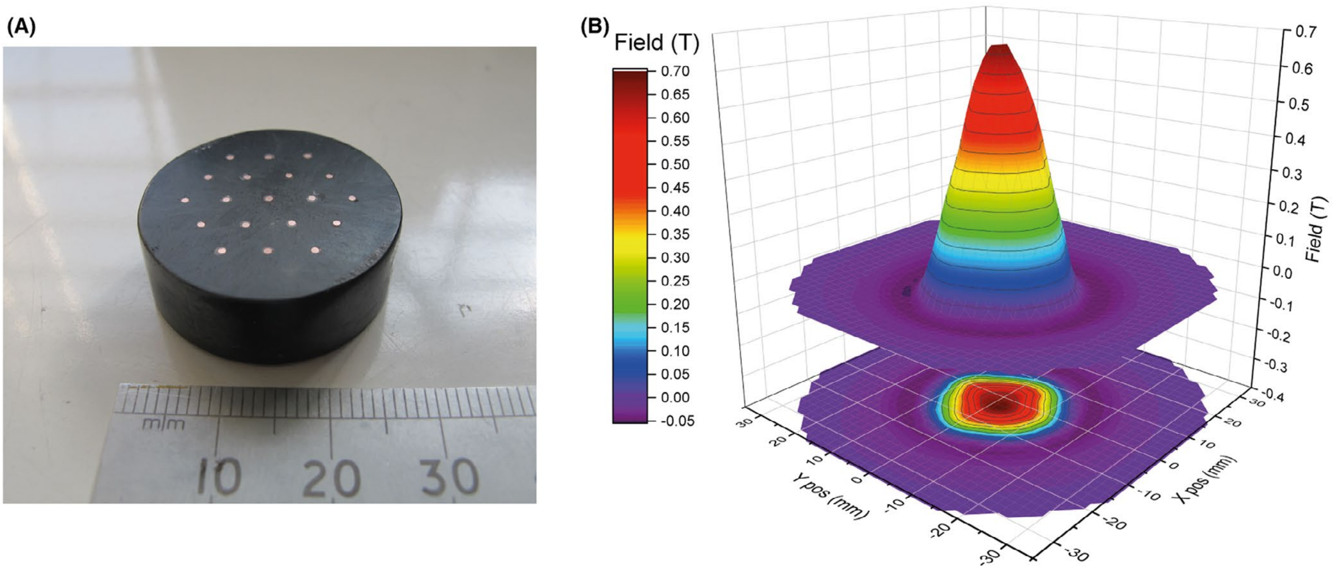

FIGURE 7 (A) Single grain thin-wall YBCO sample used in the field cooling experiments. The artificial holes were filled with copper wires and solder to minimize stress concentration and to assist cooling during magnetization. The sample contained 19 holes, each around 0.8–1.0 mm in diameter (2.6% of the cross-sectional area). (B) Trapped field profile, measured at 77 K, of the thin-wall YBCO sample. It is evident the large number of artificial holes did not affect the trapped field capability since the peak field was consistent with that observed for standard YBCO samples of the same size and the field profile remains both sharp and conical

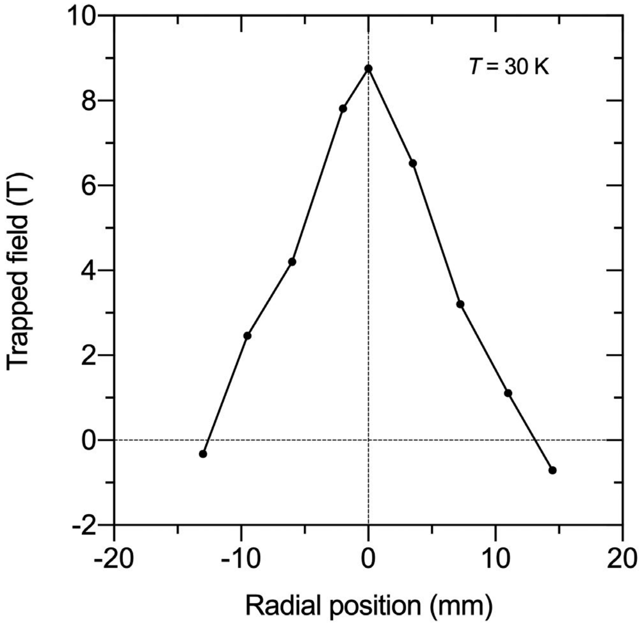

FIGURE 8 Trapped field at the surface of the 27 mm diameter thin-wall single grain YBCO sample when magnetized with 11 T at 30 K. The sample was not reinforced by an external ring

The results are significant for a number of reasons. First, it has been demonstrated the thin-wall single grain YBCO sample could indeed survive more extreme magnetizing conditions and larger electromagnetic stresses, which is consistent with the results of the mechanical tests. The presence of the artificial holes enables beneficial post melt processing treatments to further enhance the mechanical and thermal properties of these samples for potential application as trapped field magnets. For example, improved cooling and increased heat capacity by embedding copper wires could have contributed significantly to the survival of the thin-wall sample in this study. Second, the potential of the as-manufactured thin-wall YBCO sample to form a viable trapped field magnet in the sub-10 T field range has been demonstrated, since the sample was able to trap successfully 8.8 T at 30 K at its surface without any external ring reinforcement. On the other hand, the standard YBCO sample could trap only 7.6 T under similar conditions and failed when magnetized with 10 T at 35 K. This could make thin-wall YBCO an attractive option in applications where ring reinforcement may be undesirable, that is, where sample size and geometry is a major constraint.

4 | CONCLUSIONS

Indirect tensile tests were carried out on whole single grain standard and thin-wall YBCO bulk superconductors, which showed the thin-wall samples were at least 62% stronger than the standard disks due to reduced porosity in the vicinity of the pre-defined artificial holes. The mechanical strength of the samples was increased significantly by up to 93% by filling the holes with Stycast epoxy resin. This enhancement could, in theory, be increased even further by a combination of optimizing the hole pattern (and hole spacing) and choice of mechanical (and thermal) reinforcement materials.

Representative single grain samples were subsequently subjected to high-field magnetization processes to confirm the improved mechanical reliability of the thin-wall YBCO single grains. The standard YBCO sample failed when magnetized with 10 T at 35 K, whereas the thin-wall YBCO sample survived all magnetization cycles, including a maximum magnetization field of 11.5 T at 35 K. In the process, the thin-wall sample achieved successfully a surface trapped field of 8.8 T at 30 K (with potential for even higher trapped fields since it did not fail in any of the cycles) without any other form of reinforcement, as compared to 7.6 T for the standard YBCO sample.

In conclusion, we have demonstrated that the thin-wall approach is a practical route to improving the tensile strength, and therefore field trapping capability, of single grain (RE)BCO bulk superconductors.

The magnetization results are also in good agreement with estimates of the failure fields derived from the Brazilian test, further confirming that the Brazilian test is a useful technique for determining accurately the limitations of single grain (RE)BCO bulk superconductors for practical applications.

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DATA AVAILABILITY STATEMENT

All data related to this publication are available at the University of Cambridge data repository: https://doi.org/10.17863/CAM.66844.

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