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Mechanical properties of Y–Ba–Cu–O blocks welded by silver added Y–Ba–Cu–O solder

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Abstract

We have performed tensile tests at room temperature for Y–Ba–Cu–O bulk superconductors with artificial grain boundaries, which were fabricated by a joining technique using Ag added Y–Ba–Cu–O solder. The tensile strength of the joint was lower than that of the mother block Y–Ba–Cu–O. Microstructural analyses revealed that a residual liquid phase was observed in the vicinity of the interface between the mother block and the solder in the *ac*-plane. Cross-sectional observation for the samples after the tensile tests showed that the fracture occurred along the residual liquid phase. Hence, the residual liquid phase was responsible for the lower tensile strength.

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Keywords: Mechanical property; Joint; Y–Ba–Cu–O; Y–Ba–Cu–O/Ag; Welding; Solder

1. Introduction

Recent advances in melt processing techniques enabled us to produce large grain bulk RE–Ba–Cu–O superconductors (RE: rare earth elements) [1]. However, grain enlargement requires a long processing time, which causes contamination from the substrate and thereby the degradation of superconducting properties. This is evidenced by the

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fact that the maximum trapped field of Y–Ba–Cu–O disk of 100 mm diameter was about 0.8 T, which was lower than that of the disk 40 mm in diameter. In order to overcome such a problem, joining techniques have been proposed by several authors [2–5]. We have already reported that a strongly-coupled joint can be synthesized with the control of crystal growth direction along the $\langle 110 \rangle$ combined with the employment of a highly dense sintered plate as solder materials [2,3]. Furthermore, two Y–Ba–Cu–O disks fabricated in different batches were successfully joined by using Ag added Y–Ba–Cu–O as a joining reagent [3,6].

When a bulk superconductor is magnetized, electromagnetic forces are exerted along a radial direction. If the force exceeds the mechanical strength of the bulk superconductor, it will fracture. Hence the field trapping capability is limited by the mechanical strength rather than the critical current density (J_c). Many researchers therefore have investigated the mechanical properties of bulk superconductor with the aim of improving the mechanical strength. It is thus important to measure mechanical properties of joined samples, for which only few reports have been published [7].

In this paper, we thus investigated the mechanical properties of Y–Ba–Cu–O with artificial grain boundaries by means of the tensile tests at room temperature with focus placed on the relationship between the test results and the microstructure.

2. Experimental

$YBa_2Cu_3O_y$ (Y123) and Y_2BaCuO_5 (Y211) powders were prepared from Y_2O_3, BaO_2 and CuO powders via a solid-state reaction. Single domains of Y–Ba–Cu–O (Y123:Y211 = 3:1, 0.5 wt% of Pt) with dimensions of 25 mm in diameter and 12 mm in height were fabricated by the top-seeded melt-growth process [8]. Semi-circle shape of bulk samples with the joining surface perpendicular to $\langle 110 \rangle$ direction was cut from melt grown Y–Ba–Cu–O blocks.

Silver added Y–Ba–Cu–O (hereafter Y–Ba–Cu–O/Ag) solder material was prepared from Y123, Y211, Pt and Ag_2O powders. Here, in order to improve the superconducting properties of the solder material, Y211 powders were refined by ball milling. The resultant powders were weighted to have a nominal ratio of Y123:Y211 = 3:1 with additions of 0.5 wt% of Pt and 10 wt% of Ag_2O. Mixed powders were pressed into the pellets 30 mm in diameter and 15 mm in height with uniaxial pressing and then consolidated with cold isostatic pressing under a pressure of 200 MPa. The green compact was sintered at 961 °C for 10 h in air. A sliced sintered plate 0.5 mm in thickness was sandwiched by two Y–Ba–Cu–O blocks with the surfaces perpendicular to the $\langle 110 \rangle$ direction. The samples were heated to 900 °C for 3 h, heated to 995 °C for 1 h, kept for 10 h, slowly cooled to 945 °C for 100 h and finally cooled to room temperature. The whole process was conducted in air. In order to investigate the effect of Y211 and Ag addition on the tensile strength, we also prepared Y–Ba–Cu–O containing fine Y211 (hereafter Y–Ba–Cu–O/BM) and Y–Ba–Cu–O/Ag. The samples for tensile tests with dimensions of $3 \times 3 \times 4$ mm^3 were cut from Y–Ba–Cu–O block welded with Y–Ba–Cu–O/Ag (joint-Ag) and single domain of bulk samples. Then the samples were oxygenated in a temperature range of 400–500 °C. Here, the samples subjected to the tensile tests are tabulated in Table 1.

Table 1
Sample name and experimental conditions (used in this study)

Sample name	Y123:Y211	Condition of Y211	Additives
Y–Ba–Cu–O	3:1	As calcined	Pt
Y–Ba–Cu–O/Ag	3:1	As calcined	Pt and Ag
Y–Ba–Cu–O/BM	3:1	Ball milling	Pt
Joint-Ag (solder)	3:1	Ball milling	Pt and Ag
Joint-Ag (solder)	3:1	As calcined	Pt

Tensile tests were performed at room temperature. The specimens glued to two aluminum alloy rods with epoxy resin were loaded through the universal joint. The crosshead speed of the testing machine was 0.15 mm/min. Here loading direction corresponds to the longitudinal direction of the specimens, i.e., ⟨1 1 0⟩ direction. The details of the loading method are described elsewhere [9–11]. Microstructure was observed with an optical microscope. The volume fraction and the size of Y211 particles were quantitatively analyzed using an image-processing software (Mac-scope).

3. Results and discussion

3.1. Tensile tests

Fig. 1 shows the tensile strengths for Y–Ba–Cu–O, Y–Ba–Cu–O/Ag, Y–Ba–Cu–O/BM and the joint welded using Y–Ba–Cu–O/Ag (hereafter joint-Ag) at room temperature. For comparative study, the result of the tensile strength for the joint using an Er–Ba–Cu–O solder (hereafter joint-Er) [7] is also shown in Fig. 1. Open symbols are for the data where the samples did not fracture but separated from the rod. The mean value for the joint-Ag was lower than those of Y–Ba–Cu–O, Y–Ba–Cu–O/Ag and Y–Ba–Cu–O/BM that are free from grain boundaries. Furthermore, the tensile strength of the joint-Ag was similar to that of the joint-Er.

In general, it is well known that the mechanical properties of bulk superconductors are improved by Ag addition, since Ag addition decreases the number of voids, which leads to the suppression of cracking [12–15]. Likewise, we could see that the Ag addition certainly enhanced the tensile strength as presented in Fig. 1. The fact that the tensile strength of the joint-Ag was not improved compared to the joint-Er implies that the strength was

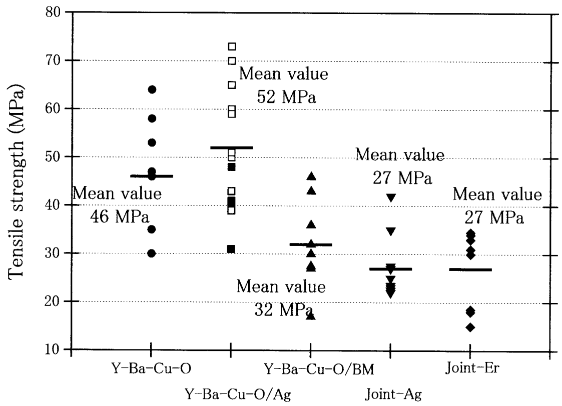

Fig. 1. Results of the tensile tests for YBCO, YBCO/Ag, YBCO/BM, joint-Ag and joint-Er [7] at room temperature. Loading direction is ⟨1 1 0⟩. Open symbols are for the data where the samples did not fracture but separated from the rod. Hence the actual tensile strength is higher than the mean value.

Table 2
Volume fraction and the average radius of Y211 particles for Y–Ba–Cu–O and Y–Ba–Cu–O/BM

	Y–Ba–Cu–O	Y–Ba–Cu–O/BM
Volume fraction	27.9%	14.0%
Radius of Y211 (μm)	1.039	0.552

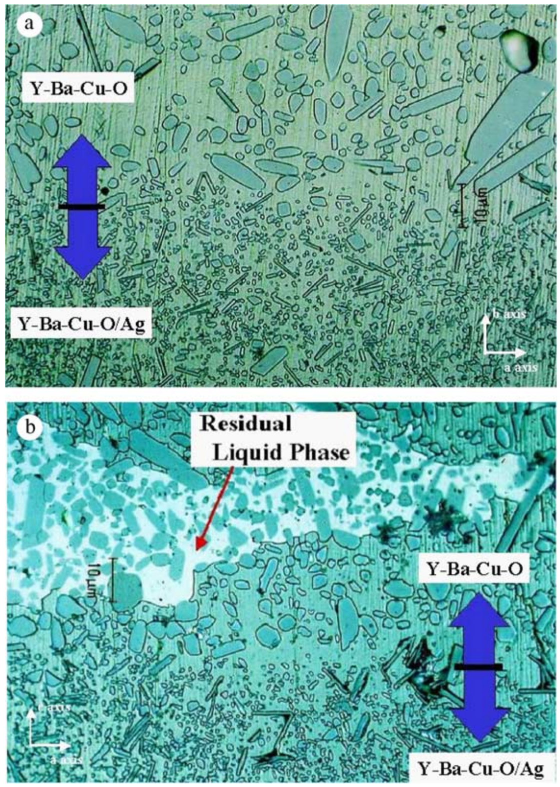

Fig. 2. Optical micrograph of the joint-Ag before tensile tests observed for (a) *ab*-plane and (b) *ac*-plane.

depressed by the addition of fine Y211 particles. It is also supported by the result that the average mechanical strength of Y–Ba–Cu–O/BM is lower than that of Y–Ba–Cu–O. Here, in order to clarify the effect of Y211 on the tensile strength, the volume fraction and mean radius of Y211 particles were investigated, and the results are tabulated in Table 2. It is evident that the volume fraction of Y211 in Y–Ba–Cu–O/BM is lower than that of Y–Ba–Cu–O. This is explained in terms of the pushing and trapping phenomena [16] of the particles during the crystal growth in that small particles tend to be pushed away from the growth front. According to the previous report [11], mechanical strength was improved with increasing the volume fraction of Y211. Hence, we believe that poor tensile strength of Y–Ba–Cu–O/BM is ascribed to a small volume fraction of Y211 particles.

3.2. Origin of fracture

Fig. 2 shows the microstructure of the joint-Ag observed for the *ab* and *ac*-planes. From these micrographs, two regions have different contrast: one is Y–Ba–Cu–O mother block with large Y211 inclusions; and the other is the joint with small Y211 inclusions. One can also see that the joint observed for the *ab*-plane is free from the defects such as residual liquid phase and the segregation of Y211. In contrast, for the *ac*-plane, residual liquid phase is observed in the vicinity of the interface between the mother block and the solder, although no defect was observed in the joined region.

Fig. 3 shows an optical micrograph of the joint-Ag observed for the *ac*-plane after the tensile tests. One can notice that the sample fractured along the residual liquid phase in the vicinity of the interface between the mother block and the solder. According to our previous studies [7], the joint-Er always fractured at the center of the joint where

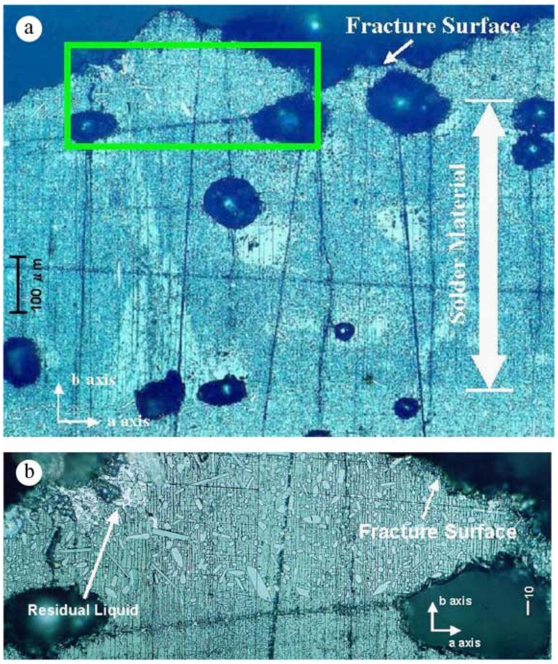

Fig. 3. (a) Cross-sectional view for the joint-Ag after the tensile tests. (b) The image at higher magnification.

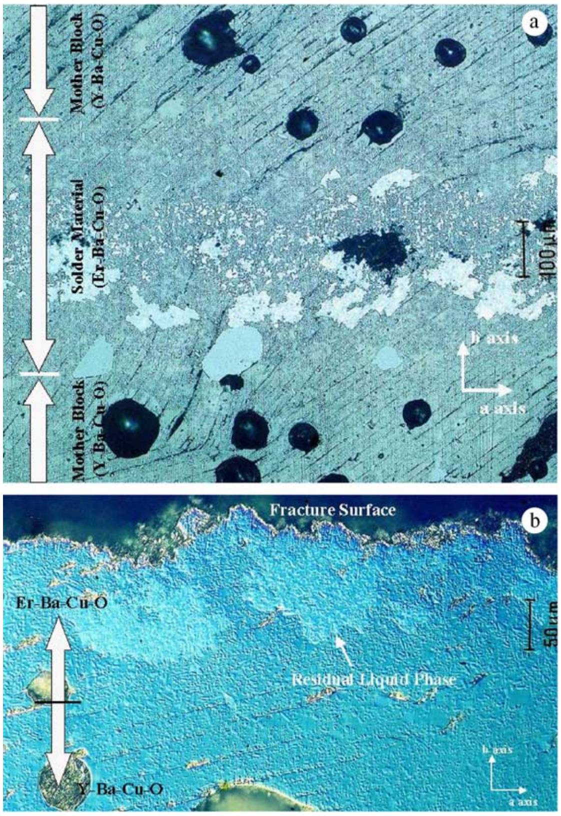

Fig. 4. Optical micrographs of the joint-Er observed for *ab*-plane (a) before the tensile tests and (b) after the tensile tests [7].

the local segregation of Er211 and residual liquid phase were present as shown in Fig. 4. These results support the idea that the local segregation and residual liquid phase are the main source of poor mechanical properties.

4. Summary

We have carried out the tensile tests for joined Y–Ba–Cu–O disks with artificial grain boundaries. The tensile strength of the joint welded using Y–Ba–Cu–O/Ag solder and Er–Ba–Cu–O solder than that of Y–Ba–Cu–O bulk superconductor. From microstructural analyses the residual liquid phase was the source of cracking. Hence, the mechanical properties of the joint will be improved if one can avoid the presence of the residual liquid phase.

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