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# Single-domain NEG bulk superconductors for high magnetic field applications

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**Abstract**

Single-domain (Nd, Eu, Gd)–Ba–Cu–O bulk superconductors, silver free and with 10 wt.% of silver, were prepared with the oxygen-controlled melt-growth process. Seeding techniques were used to promote single-grain growth with controlled orientation using a melt-textured Nd-123 as a seed. The trapped field in the (Nd, Eu, Gd)–Ba–Cu–O bulk of 22 mm diameter and 9 mm thickness was measured at 77 K after field cooled in 7 T. The trapped-field profile was measured by means of a Hall probe at the distance of 5 mm from the sample surface. A single and multiple peaks were observed on (Nd, Eu, Gd)–Ba–Cu–O samples with and without silver addition, respectively. In the sample with silver, a maximum trapped field of 0.5 T was achieved at 3 T after the field reduction from 7 T. © 2001 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

Successful bulk superconductor applications are strongly linked to the improvement of their mechanical properties together with their flux pinning capability. Large bulk superconductors can trap much larger magnetic fields than conventional permanent magnets [1]. Taking advantage of our expertise in the production of melt-processed bulk materials [2–4], our group proposed the replacement of low-$T_c$ superconducting coils by high-$T_c$ bulk materials in magnetically levitated vehicles (MAGLEV). For this application, the trapped field of bulk superconductors plays a key role. It is proportional to the magnetic moment of the superconductor, which in turn is proportional to the intra-grain critical current density ($J_c$) and to the current loop size ($d$). For this purpose, recently developed NEG-123 bulk superconductors with high pinning performance are the best-suited choice [4,5].

In this paper we present preliminary results of our attempts to grow single-grain NEG-123 pellets using the oxygen-controlled melt-growth (OCMG) process with mechanical properties improved by an addition of silver oxide.

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## 2. Experimental

High-purity commercial powders (5N) of ($Nd_{0.33}$-$Eu_{0.33}Gd_{0.33})Ba_2Cu_3O_y$, Nd-422, Eu-211 and Gd-211, were weighed to have a nominal composition of $(Nd_{0.6}Eu_{0.6}Gd_{0.6})Ba_{2.4}Cu_{3.6}O_y$. 0.5 mol% Pt was added to refine size of secondary phase particles. In order to improve mechanical properties, 10 wt.% of $Ag_2O$ powders were also added to the final precursor. Heat treatment profiles in the melt process for the NEG-123/NEG-211 composites were scheduled on the basis of the DTA results. The well-mixed powders were uni-axially pressed into pellets of 30 mm diameter and subjected to a cold isostatic pressing under 2000 kg/cm$^2$.

Single-grain (Nd, Eu, Gd)–Ba–Cu–O samples were grown in a tube furnace with the OCMG process combined with a top-seeded melt-growth technique, the details of which are reported elsewhere [6]. The seed crystal was dropped onto the sample surface above the peritectic temperature, at $T_p + 20°C$.

For trapped-field measurements we used a 10 T superconducting magnet consisting of NbTi and $Nb_3Sn$ coils cooled by a cryocooler with a room temperature bore of 10 cm in diameter. First, the sample was cooled to liquid nitrogen temperature (77 K) in the presence of 7 T directed parallel to the *c*-axis. The trapped-field distribution was measured with a scanning Hall probe sensor at 5 mm above the sample surface as the external field was reduced from 7 to 0 T with 1 T step. The details of the measurement procedure are described elsewhere [7].

## 3. Results and discussion

### 3.1. Microstructure of melt-grown NEG-123

Fig. 1 shows optical micrographs of single-domain (Nd, Eu, Gd)–Ba–Cu–O: (a) silver-free and (b) with 10 wt.% of $Ag_2O$. The size of the single-domain area almost coincided with the dimension of the entire sample, and was about 23 mm in diameter. It is also evident that the grain grew from the seed towards the sample edges, which is evidenced by the orthogonal crystallographic growth lines extended on the entire surface of the sample. Thus we proved that single-grain bulks can be produced with the composition of NEG-123 + 40 mol% NEG-211 + 0.5 mol% Pt by optimizing the growth conditions.

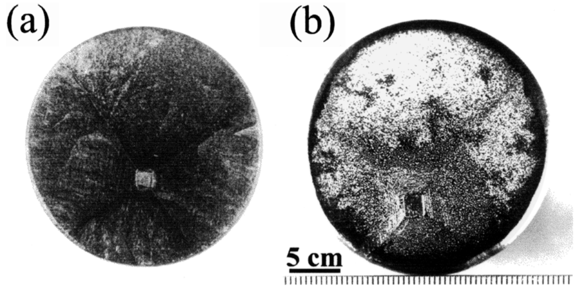


Fig. 1. Optical micrographs of (Nd, Eu, Gd)–Ba–Cu–O (NEG-123 with 40 mol% of NEG-211 and 0.5 mol% of Pt): (a) silver free and (b) with 10 wt.% of $Ag_2O$.

### 3.2. Trapped-field measurements

Fig. 2(a) shows the trapped magnetic field distribution for the Ag-free (Nd, Eu, Gd)–Ba–Cu–O sample. For this measurement, the sample was field cooled at 5 T in liquid nitrogen. The trapped field was measured by scanning a Hall sensor with a small active area of 0.5 mm$^2$. In Fig. 2(a) serious weak links can be identified along the $\langle 100 \rangle$ growth direction and also at the center. We believe that the mechanical stresses during cooling and magnetization caused cracking.

The same experiments were performed with 10 wt.% Ag samples and the results are presented in Fig. 2(b) and (c). Both samples had similar compositions, but the melt growth was performed in different gas atmospheres, namely Ar–1% $O_2$ and Ar–0.1% $O_2$. The magnetization process for the first sample prepared in 1% $O_2$ was the same as before, in that the sample was field cooled to liquid nitrogen temperature at 5 T and after the external field was switched off, the trapped field was measured. The field distribution in Fig. 2(b) has a single peak, showing that no weak links are present in this sample. This experiment proves that the Ag addition is effective in improving the mechanical properties of OCMG processed (Nd, Eu, Gd)–Ba–Cu–O materials.

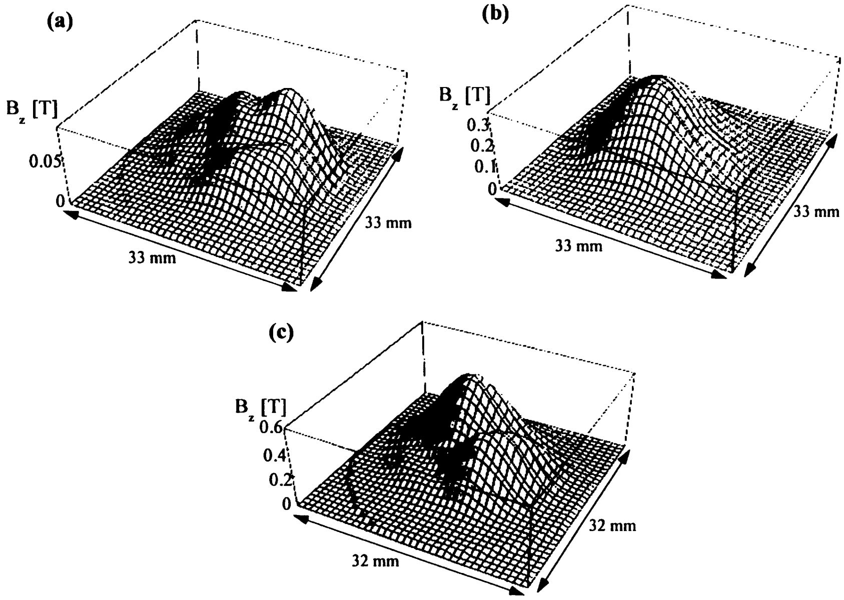


Fig. 2. The trapped-field distribution of NEG-123 + 40 mol% of NEG-211 with 0.5 mol% of Pt samples at 77 K (the remnant state): (a) silver-free-processed in Ar– 0.1% $O_2$; (b) 10 wt.% $Ag_2O$ processed in Ar–1% $O_2$; (c) 10 wt.% $Ag_2O$ and processed in Ar–0.1% $O_2$.

The second sample, prepared in 0.1% $O_2$ atmosphere, was field cooled to $LN_2$ temperature at 7 T. The trapped field was measured at several stages as the external field was decreased from 7 to 0 T at 0.5 T interval. In Fig. 2(c) one can see two superconducting domains, which reflects the crack formation during the magnetization process. We can suppose that the electromagnetic forces were too large in this particular case, which resulted in the fatal fracture [8].

The field dependence of the maximum trapped-field $B_0$ is presented in Fig. 3. It is notable that the trapped-field value is almost constant in the field range from 0.5 to 3.5 T. This result is in accord with the $J_c$–$B$ properties reported earlier [9]. It is also notable that trapped magnetic fields of 0.5 and 0.45 T are achieved at 77 K for the applied fields of 3 and 4 T, respectively. In this case the sample dimensions were slightly smaller, and 22 mm in diameter and 9 mm in thickness. High field-trapping capability of this sample even at high magnetic fields implies that (Nd, Eu, Gd)–Ba–Cu–O bulk superconductors can trap much higher fields, if one can fabricate larger samples.

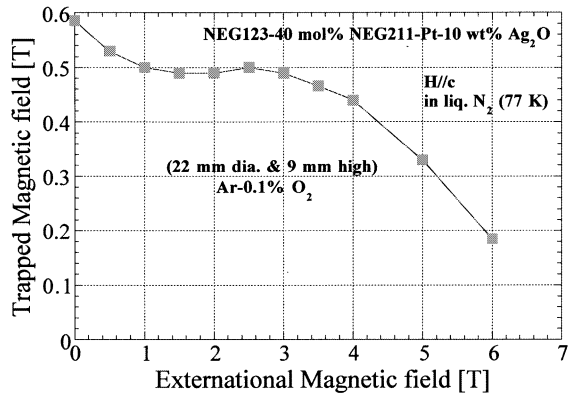


Fig. 3. Trapped field versus applied field in NEG-123 + 40 mol% of NEG-211 + 0.5 mol% of Pt with 10 wt.% of $Ag_2O$ at 77 K. The sample was melt processed in Ar–0.1% $O_2$.

## 4. Conclusion

We have succeeded in growing *c*-axis oriented (Nd, Eu, Gd)–Ba–Cu–O samples 22 mm in diameter and 9 mm in thickness using the OCMG process. The trapped-field measurements proved that Ag addition was effective in reducing weak links and cracking. In addition, (Nd, Eu, Gd)–Ba–Cu–O with 10 wt.% $Ag_2O$ prepared in 0.1% $O_2$ atmosphere showed high trapped fields of 0.5 T at 3 T even in a fractured condition.

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## References

[1] R. Weinstein, Y. Ren, M. Eisterer, H.W. Weber, Proc. 8th US–Japan Workshop, 1997.
[2] M. Murakami, Prog. Mater. Sci. 38 (1994) 311.
[3] M. Murakami, Melt Processed High-Temperature Superconductors, World Scientific, 1992.
[4] M. Muralidhar, M.R. Koblischka, T. Saitoh, M. Murakami, Supercond. Sci. Technol. 11 (1998) 1349.
[5] M. Muralidhar, M.R. Koblischka, P. Diko, M. Murakami, Appl. Phys. Lett. 76 (2000) 91.
[6] M. Muralidhar, T. Miyamoto, M. Murakami, Supercond. Sci. Technol. 13 (2000) 756.
[7] T. Miyamoto, J. Katagiri, K. Nagashima, M. Murakami, IEEE Trans. Appl. Supercond. 9 (1999) 2066.
[8] Y. Ren, R. Weinstein, J. Liu, R.P. Sawh, C. Foster, Physica C 251 (1995) 15.
[9] M. Muralidhar, M.R. Koblischka, M. Murakami, Physica C 313 (1999) 232.