The successful incorporation of Ag into YBa$_2$Cu$_3$O$_7$ bulk superconductors

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Overview

- Motivation
- Growth of YBCO-Ag
- Growth rate
- Microstructure and Composition
- Trapped field
- Conclusions
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Motivation for incorporation of Ag

- Mechanical properties limit achievable superconducting properties
- Ag improves the fracture toughness and bending strength without negatively affecting superconducting properties
- YBCO, GdBCO-Ag and SmBCO-Ag successfully batch processed
- Reduction in peritectic temperature affects initial decomposition, diffusion, interface kinetics & growth rate
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9 samples successfully partially grown by liquid-phase enriched TSMG
Growth of YBCO-Ag by CCIH

- Continuous cooling and isothermal hold (CCIH) technique
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Growth Rate of YBCO-Ag

- **Isothermal holding:**
  \[ G = \alpha (\Delta T)^\beta \]
  *(Endo, Chauhan et al. 1996, Zhai, Shi et al. 2014, Shi, Babu et al. 2007)*

- **Some growth in continuously cooled region:**
  \[ G = \frac{dL}{dt} \]
Growth Length

- \[ L = \int_{t_{\text{start}}}^{t_{\text{end of continuous cool}}} G_{\text{continuous cool}} \, dt + G_{\text{isothermal hold}} \, t_{\text{isothermal hold}} \]

- \[ L = \int_{t_{\text{start}}}^{t_{\text{end of continuous cool}}} \alpha (-0.5t)^\beta \, dt + \alpha (\Delta T)^\beta \, t_{\text{isothermal hold}} \]
# Samples

<table>
<thead>
<tr>
<th>$\Delta T$ (hours)</th>
<th>$t_i$ (hours)</th>
<th>Top of sample</th>
<th>Cross section of sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
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</table>

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<tr>
<th>$\Delta T$ (hours)</th>
<th>$t_i$ (hours)</th>
<th>Top of sample</th>
<th>Cross section of sample</th>
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<tbody>
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<td>0.75</td>
<td><img src="image17" alt="Image" /></td>
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</table>
Growth Rate Model

\[ G_{a/b} = 1.4 \times 10^{-3}(\Delta T)^{1.76} + 0.035 \]

\[ G_c = 4.5 \times 10^{-3}(\Delta T)^{1.42} + 0.035 \]

\[ T_p = 970^\circ C \]

\[ R_{a/b}^2 = 0.998 \]

\[ R_c^2 = 0.997 \]
Use of CCIH

- Silver deficient region
- Offset in growth rate model

\[ G_{a/b} = 1.4 \times 10^{-3} (\Delta T)^{1.76} + 0.035 \]
\[ G_c = 4.5 \times 10^{-3} (\Delta T)^{1.42} + 0.035 \]
Derivation of a heating profile

Temperature

Time

969°C, 0.5°C/h
946°C, 100°C/h
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Microstructure in c-axis direction

0 mm 1 mm 2 mm 3 mm 4 mm

5 mm 6 mm 7 mm 8 mm 9 mm
Composition in c-axis direction

- Normalised at%
- Distance from seed (mm)
- Y
- Cu
- Ba
- Ag
- Stoichiometric Y
- Stoichiometric Cu
- Stoichiometric Ba
- Stoichiometric Ag
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## Trapped field

<table>
<thead>
<tr>
<th></th>
<th>YBCO-Ag</th>
<th>YBCO</th>
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</thead>
<tbody>
<tr>
<td><strong>Top</strong></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>Max</td>
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<tr>
<td></td>
<td>0.643 T</td>
<td>0.652 T</td>
</tr>
<tr>
<td><strong>Base</strong></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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<tr>
<td></td>
<td>Max</td>
<td>Max</td>
</tr>
<tr>
<td></td>
<td>0.366 T</td>
<td>0.440 T</td>
</tr>
</tbody>
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Conclusions

- Growth rate of YBCO-Ag has been studied in detail using the new CCIH technique.
- A model for the growth rate of YBCO-Ag in both the a/b- and c-axis direction has been developed.
- This growth rate model has enabled a heating profile to be developed to successfully grow single grains upto 30 mm in diameter.
- We are now able to grow large single grains of YBCO-Ag which exhibit uniform trapped fields.