Obtention and characterization of YBCO/Ag/YBCO welds at different misorientation angles

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Abstract. The microstructural and magnetic properties of YBa$_2$Cu$_3$O$_7$ (YBCO) welds with different crystallographic [001]-tilt misorientation, prepared by the Ag surface melting induced welding technique, have been studied. The inter- and intra-grain critical current densities have been simultaneously obtained by solving the Inverse Problem from the remanent local magnetization magnetic field maps measured by Hall Probe imaging. The obtained dependence of the inter-grain current density with the angle, $J_c^{\text{GB}}(\theta)$, is compared to previous results for thin-film bicrystals and bulk boundaries.

1. Introduction
The fabrication of large, complex shaped YBCO pieces for superconducting systems like magnetic bearings, rotors, flywheels, etc. may require superconducting joining of different YBCO single domains with a specific misorientation angle, thus creating artificial grain boundaries. This fact arises the need to study the effects of those misorientations. Several techniques have been proposed to grow-together or join different YBCO joints, such as the multiseeding technique [1], the direct contact method [2] or the welding of different single domains using several lower melting point agents [2-6]. In the past, we developed in our group a surface melting welding technique induced by the use of a metallic Ag film in between the tiles to be joined. This technique, which already proved to deliver high quality non-misoriented welds [6, 7], has now been adapted in order to fabricate both symmetric and asymmetric YBCO/Ag/YBCO welds with different [001]-tilt misorientations. For each case, the intergrain ($J_c^{\text{GB}}$) and intragrain ($J_c^{\text{G}}$) critical current densities have been evaluated using an inductive methodology recently described [8]. The obtained $J_c^{\text{GB}}(\theta)$ angular dependence is discussed in the scope of previous published results.

2. Sample preparation and microstructure
The [001]-tilt boundaries were prepared using the silver welding methodology developed in our group [6, 7]. The method consists basically of assembling a metallic 10 μm thick Ag foil in between the two tiles to be joined in a sandwich-like configuration. The specimen is then first heated up to $T_{\text{max}}=995^\circ$C and dwelt for 3 hours; then it follows a slow-cooling from $T_i=980^\circ$C down to $T_2=950^\circ$C and last it is fast-cooled to room temperature. Finally, the welded sample is annealed in flowing oxygen at 1.1 bar for 120 hours at $T_{\text{ox}}=450^\circ$C.

The actual misorientation angle was determined from the observation of the twin plane families at
both sides of the boundary on an ab plane with the help of an optical microscope with polarized light. The accuracy of the result was in agreement with four-pole X-Ray measurement, where we confirmed in addition that samples contained no twist component in the misorientation. Both symmetric and asymmetric [001]-tilt boundaries were prepared, with angles ranging from 2 to 20 degrees.

Figure 1 shows an example of the observed ab plane for a symmetric $\theta=13^\circ$ weld. For clarity, the position of the boundary has been indicated with the dotted line. The twin plane families at both sides of the junction can be appreciated (dashed lines). Observe that the boundary is free of secondary phases or voids, indicating the success of the joining process. It is noticeable that the boundary surface has a non-straight structure, although the original surfaces to be joined were carefully polished. This fact indicates that the structure formed during the recrystallization of the surface at the growth stage of the process.

3. Electromagnetic characterization

The magnetic characterization of the samples was carried out with an in-field Hall probe scanning system developed in our lab \cite{9, 10}. The gap between the Hall probe and the measured surface is 80-100 $\mu$m and the spatial resolution is 160 $\mu$m. The remanent $B_r(x,y)$ was measured after field-cooling the welded samples to 77 K under a field of 6000 gauss, applied parallel to the c axis. Figure 2a shows an example of the $B_r-H$ map obtained from Hall probe imaging. The depression of the superconducting performance at the position of the boundary is clearly appreciated.
The $J_{c}^{GB}$ and the $J_{c}^{G}$ components are determined from the current distribution map $J_{c}(x,y)$ maps obtained from the remanent Hall magnetic map using an Inverse Problem solver ("Caragol" [11]), using a methodology recently described [8]. Figure 2b exemplifies the determination method, which uses the critical current density component perpendicular to the junction ($J_{y}$). By tracing a profile parallel to the junction far from the junction along the a and b peaks (profile 1) or c and d (profile 3), the $J_{c}^{G}$ values are obtained. With the help of the profile 4, the junction position is placed (peak e) and finally, using peaks f and g on profile 2, the $J_{c}^{GB}$ values are determined.

Figure 3a shows the angular dependence of the $J_{c}^{GB}/J_{c}^{G}$ ratio for both symmetric and asymmetric misorientations obtained in this way. Three additional crystallographically aligned welds ($\theta=0^\circ$) have been included as a reference. Within the reproducibility of the welding method, no significant difference can be appreciated between the symmetric and asymmetric cases.

Figure 4 summarizes the angular $J_{c}^{GB}(\theta)$ dependence we found and previously reported results on bulk boundaries [12-16] and thin-film bicrystals [17-20] prepared by different methods. [12-21]. The $J_{c}^{GB}(\theta)$ behavior we found is clearly in agreement with other studies on bulk boundaries (open symbols), in spite the fabrication methods and the $J_{c}^{GB}$ determination (usually transport) were different. As earlier reported, it can be appreciated that for low-angles the $J_{c}^{GB}$ and relative $J_{c}^{GB}(\theta)$ dependence of bulk boundaries are smaller than that of thin-film bicrystals, whereas for high-angles the inter-granular current densities of both systems tend to merge.

It has been suggested that the plateau observed in the $J_{c}^{GB}(\theta)$ dependence of bulk boundaries at low angles would be given by the magnetic interaction of the grain-boundary vortices with the Abrikosov vortices in the banks [13]. At high-angles, the pinning of inter-granular vortices at defects in the boundary self might rule the $J_{c}^{GB}(\theta)$ behavior. A long-junction, flux pinning scenario has been speculated, according to which the observed meandering thin-film bicrystals would provide a stronger pinning than the virtually "perfect" or large-faceted bulk boundaries offering a weaker-pinning [22]. However, a higher pinning force might be generated at the bulk boundary, due to the variation of the magnetic energy of the vortices by twin boundaries, explaining the relative high $J_{c}^{GB}$ sometimes observed for high angle bulks [13]. It is clear that the subject is a complex issue that still requires further investigation for a complete understanding. Measurements of the inter-grain critical current density as a function of the applied field at different angle regimes, which might provide clues onto the pinning mechanisms, are currently under investigation in our group.

4. Conclusions
Symmetric and asymmetric [001]-tilt YBCO/Ag/YBCO artificial bulk boundaries have been successfully prepared and characterised. The $J_{c}^{GB}$ and $J_{c}^{G}$ critical current densities have been...
determined using an inductive methodology recently introduced. The $J_{c}^{GB}(\theta)$ angular dependence found has been compared to similar studies on bulk and thin-film boundaries. Our results are in agreement with $J_{c}^{GB}(\theta)$ results found for bulk boundaries prepared and measured in different ways, and show a smaller $J_{c}^{GB}$ and weaker dependence of the critical current density across the grain boundary than that observed for thin films.

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