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Designing high-performance superconductors with nanoparticle inclusions: comparisons to strong pinning theory[1]

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The current carrying capacity J_c of type-II superconductors is severely limited by dissipation from the motion of vortices, magnetic flux lines that appear inside these materials upon exposure to sufficiently high magnetic fields. Incorporating nanoparticle inclusions into superconducting films is a well-established route for boosting J_c because defects can trap vortices. However, these inclusions reduce the overall superconducting volume and can strain the interlaying superconducting matrix, which can detrimentally reduce the critical temperature T_c. Consequently, an optimal balance must be achieved between the nanoparticle density n_p and size d. Determining this balance requires garnering a better understanding of vortex-nanoparticle interactions, described by strong pinning theory. Here, we map the dependence of the critical current on nanoparticle size and density in $(Y_{0.77}Gd_{0.23})Ba_2Cu_3O_{7-\delta}$ films in magnetic fields up to 35 T, and compare the trends to recent results from time-dependent Ginzburg-Landau simulations. We identify consistencies between the field-dependent critical current $J_c(B)$ and expectations from strong pinning theory. Specifically, we find that that $J_c \sim B^{-\alpha}$, where α decreases from 0.66 to 0.2 with increasing density of nanoparticles and increases roughly linearly with nanoparticle size d/ξ (normalized to the coherence length). At high fields, the critical current decays faster ($\sim B^{-1}$) suggestive that each nanoparticle has captured a vortex. Lastly, we reveal that the dependence of the rate of thermally activated vortex motion (creep rate, S) on nanoparticle size and density roughly mirrors that of α, and compare our results to low T nonlinearities in $S(T)$ that are predicted by strong pinning theory.

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