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Ordering, nanostructure and high-field magnetization of quenched and annealed metastable ilmenite-hematite solid solutions

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The ilmenite-hematite solid solution series xFeTiO$_3$-$(1-x)$Fe$_2$O$_3$ can generate extremely unusual magnetic properties in natural rocks and has been investigated for more than fifty years. Both, ilmenite (FeTiO$_3$) and hematite (Fe$_2$O$_3$) are antiferromagnetic, but intermediate compositions are either antiferromagnetic or ferrimagnetic, depending on their chemical order. Within a single sample, nano-scale variations in local composition x and ordering state Q depend on minute details of the cooling and annealing history, and have large effects on the magnetic properties, which include self-reversal of thermoremanent magnetization and large exchange bias. We present a systematic study of magnetic properties of samples in the composition range of $0.6 \leq x \leq 0.7$ with differing nanostructure and consequently differing magnetic properties. Using high-field measurements up to 7 T, together with TEM images and theoretical models we classify nanostructure formation in terms of x, Q, and characteristic size d. These characteristics are then linked to the magnetic properties. The sample characterization relies on average mean-field models of $M_s(T)$. To implement the varying Fe and Ti densities, and the distribution of Fe ions in the variably ordered solid solutions, the models either use statistical interactions between sites, whereby they effectively average over all possible configurations, or they describe specific random configurations. Statistical mean field models are successful in predicting the Curie temperatures T_C and $M_s(T)$ curves of the Ilm$x$ solid solutions. The results depend on the interaction coefficients, which either had been determined by neutron diffraction measurements (Samuelson and Shirane, 1979), by Monte-Carlo model fits (Harrison, 2006), or by density-functional theoretic calculations (Nabi *et al.* 2010). Hysteresis branches have been measured for a wide variety of samples at different temperatures 40 K, 100 K and 300 K. None of them saturate at 7 T, the strongest field available to us so far. Some of the samples show the beginnings of a pseudo-metamagnetic transition at the upper limits of the measurements. In previous models this is explained by anti-phase boundaries and exchange coupling between ordered and disordered regions with differing sizes and hence differing responses to an external field. These effects will be studied further up to 60 T using a European high-field laboratory within the EuroMagNET II/EMFL scheme.