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Reversible chain formation during magnetic hyperthermia experiments

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In addition to the AC field conditions or the particle average size, others factors, often neglected, may play a fundamental role on the heating capacity of magnetic nanoparticles during magnetic hyperthermia treatments. In particular, the organization of particles into assenblies, such as chains, as a consequence of the AC field exposure has been poorly studied. Previous theoretical works had shown the impact of chaining on the heating properties of magnetic nanoparticles [1] and very recently the formation of chains or columns along the magnetic field direction during hyperthermia experiments has been demonstrated experimentally [2].

In this work, we have used two types of particles (≈13 nm spherical and ≈26 nm octahedral) (Figure 1A) and several experimental set-ups to evaluate the chain formation over time during magnetic hyperthermia experiments. First, the particles were dispersed in a resin and this suspension was placed in a magnetic hyperthermia device with a closed coil. The alternating magnetic field was applied during 30 min. After, the sample exposed to the AC field and the control suspension was placed to a thermomixer at 60^{o}C so that the resin fully polymerized. For small particles, long chains were observed by TEM in the sample exposed to the AC field but not in the sample not exposed to the AC field (Figure. 1B). In contrast, for bigger particles, macroscopic chains were observed in the sample exposed to the AC field only. The effect of chain formation is investigating using computation model.

The dynamics of chain formation at different applied field times were studied using the 26 nm octahedral nanoparticles. An increase of the chain length over time under the exposure to the AC magnetic field was observed (Figure. 1C). Once the magnetic field was removed, chains started to break down. This chain formation during the magnetic hyperthermia measurements may be a critical parameter to consider in the study of the heating properties of magnetic nanoparticles in the frame of magnetic hyperthermia.

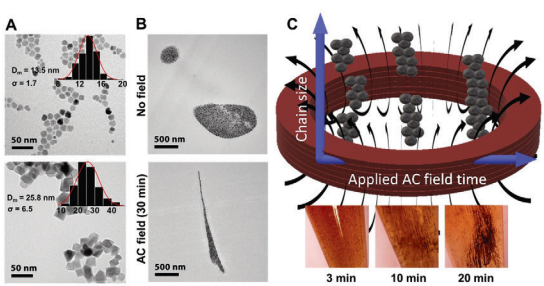

Figure 1: A) TEM images and particle size distribution of the nanoparticles used. B) TEM images of the magnetic nanoparticles (≈13 nm) in resin before and after AC magnetic field exposure C) Images of magnetic nanoparticles in resin when magnetic field is applied at different times.

(1) Balakrishnan, P. B.; Silvestri, N.; Fernandez-Cabada, T.; Marinaro, F.; Fernandes, S.; Fiorito, S.; Miscuglio, M.; Serantes, D.; Ruta, S.; Livesey, K., et al. *Advanced Materials* **2020**, *32*, 2003712.

(2) Mille, N.; De Masi, D.; Faure, S.; Asensio, J.; Chaudret, B.; Carrey, J. *Applied Physics Letters* **2021**, *119*, 022407.