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The role of the magnetocrystalline anisotropy on the frequency-dependent heating performance of magnetic nanoparticles

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Magnetic particle hyperthermia (MPH) is a novel, minimally invasive, therapeutic modality, used as a cancer treatment, that employs magnetic nanoparticles (MNPs) as the heating source [1]. Once accumulated to the tumor area, nanoparticles are exposed to an external alternating magnetic field (AMF) that causes reversal of their magnetic moments, activating mechanisms of energy deposition in the form of heat. The key measure used for characterizing the heating efficiency of nanoparticles in MPH is the specific loss power (SLP), which is usually estimated from quasi-static minor hysteresis loops [2]. However, rate-independent hysteresis is just a zero-temperature approximation where the nanoparticle's magnetic moments will jump to a new energy state only when the anisotropy barrier is reduced to zero height by the action of an external field. When thermal agitation is active, the system has a chance to overcome the barrier before its height is reduced to zero and the jump has some probability of taking place at an earlier time [3]. In addition, the chances for this to occur should be higher the lower the field rate of change, because the system spends more time in front of the barrier to overcome, a process that is also dictated by the magnitude of magnetic anisotropy [3].

The aim of this work is to present the impact of MNPs anisotropy K and AMF frequency f on the rate-dependent hysteresis loop. The area of the later is also used to estimate the SLP magnitude. The system under study is an assembly of non-interacting magnetite nanoparticles with a size of 30 nm. Micromagnetic simulations were performed by using OOMMF software package [4] to obtain the hysteresis loops under a 24 kA/m alternating magnetic field amplitude and for various frequencies (50-765 kHz) typically used in MPH. We show that hysteresis loop area increases with field rate. Moreover, the shape of nanoparticles is also considered by applying different anisotropy contributions. Perfectly spherical particles should possess only the cubic magnetocrystalline anisotropy term while a deviation from this ideal case will give rise to the presence of other easy magnetization pathways described by a uniaxial anisotropy K_u. The proposed approach considers not only the K_u, that is usually utilized in literature, but also the cubic magnetocrystalline one K_c since it is always present even with a minor role. Thus, we carried out systematic SLP vs. f trends, for different K_u values (0, 5, 10, and 15 kJ/m^3) with and without K_c (-11 kJ/m^3) at both T=0 and 300 K resulting to a different law of SLP(f) and enlightening how the frequency-dependent SLP evolves from spherical case, to a more realistic one considering an additional uniaxial term. The effect of energy-minimization dynamics was also studied by estimating loops for different damping coefficient, a, values (a=1.0, 0.1 and 0.01).

Our findings provide new insight in the validity of dynamic micromagnetic simulation to analyze the frequency behavior of SLP within the framework of rate-dependent hysteresis and indicate that anisotropy selection plays a key role in the reliability of simulations.

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