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Application of magnetic cobalt nanoparticles to enhance permeability of metal-polymer composite substrates

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High throughput printing techniques offers direct patterning and reduced material and processing costs compared to silicon technology. For example radio-frequency identification (RFID) and security codes are expected to be among the first commercially viable applications of printed electronics. To enable their sophisticated proof-of-concept structures thermoplastic magnetic substrates and magnetic inks need to be developed.

The objectives of this work were synthesis of separated magnetic nanoparticles and their influence in permeability in thermoplastic substrate as a embedded inclusions. Furthermore, expected magnetic properties as a function of filler loading were evaluated by reluctance and Bruggeman theory.

Altogether 50 g of Co nanoparticles were produced by hydrogen (H_2/N_2 23 %) reduction of cobalt chloride at the temperature of 950 $^{\circ}$C (Forsman et al. 2008). Fourier transformation infrared spectroscopy was used to monitor concentrations of reaction product HCl and gas phase impurities. Mass concentration of particles determined with filter samplings was 17 g/m^3. The number size distribution of the primary particles was determined with TEM analysis to be normal with median diameter of 76 nm and standard deviation of 20 nm.

To enable material characterisation and magnetic substrates for further testing metal-polymer composite with 5 vol.% of Co nanoparticles in a thermoplastic polymer ER182 matrix (NOF Corporation, Japan) were compounded using mixing extruder. Furthermore the samples were made by injection moulding system, details are reported elsewhere (Hu et al. 2007). The microstructure was checked by FESEM (Zeiss ULTRA plus, Germany) verifying homogenous distribution of the Co inclusions. Majority of the particles were separated but also some short particle chains were observed. Magnetic properties of the composite were analyzed with Agilent E4991A RF Impedance/Material analyzer (Agilent Technologies Inc., USA) at 1 GHz.

A simple model was developed for the effective relative permeability μ_r^{eff} of the composite substrate. The model is based on equivalence of magnetic (reluctance) and electric (resistance) circuits. The model assumes periodically distributed cubic non-interacting nanoparticles. This model is compared with the well-known Bruggeman's effective medium theory (Starostenko et al.; Ramprasad et al. 2004).

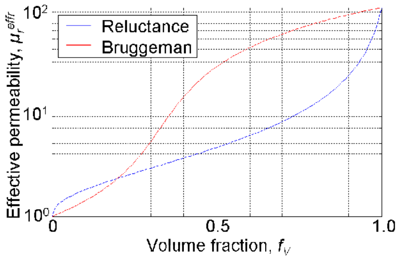

Fig. 1. Effective relative permeability as a function of nanoparticle volume fraction by the two theories. Here μ_r = 100 for Co and μ_r = 1 for the polymer.

In Fig. 1 the two theories are compared and for small volume fractions the reluctance theory becomes close to the Bruggeman theory, as expected, but for large volume fractions models exhibit a significant discrepancies. For the fabricated composites the reluctance theory gives μ_r^{eff} = 1.62 and the Bruggeman's theory 1.24 while the measured permeability was about 1.20, thus close to Bruggeman's prediction. However, taking demagnetization into account also the reluctance theory can be fitted to experiments by assuming that the particles are agglomerated with an average agglomerate aspect ratio of 2. Moreover, magnetic losses can be included in the models by using complex permeabilities.

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