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Synthesis and Characterization of Superparamagnetic Polyurethane for Advanced MPI Applications

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Abstract

Magnetically traceable polymer composites have gained increasing attention for biomedical applications. They are particularly relevant for designing materials that can be non-invasively detected and localized using magnetic particle imaging (MPI) or analyzed using magnetic particle spectroscopy (MPS). Superparamagnetic iron oxide nanoparticles (SPIONs) are of particular interest due to their excellent magnetic properties, biocompatibility, and tunable surface chemistry. The incorporation of SPIONs into polymeric matrices such as polyurethane (PU) enables the creation of flexible, biocompatible, and magnetically active materials. Polyurethane is well-established in medical device manufacturing due to its favorable mechanical and chemical properties. However, the reproducible embedding of SPIONs within PU and the preservation of both magnetic and mechanical performance remain significant challenges. This study aimed to develop a systematic approach for integrating SPIONs into PU, focusing on reproducible synthesis, structural characterization, and magnetic evaluation of the resulting nanocomposites.

I. Introduction

Coatings for implants and catheters are essential to improve the biocompatibility, functionality, and long-term stability of medical devices [2]. By modifying surface chemistry and topography, undesired biological responses such as thrombosis, bacterial adhesion, and inflammation can be reduced [3]. Among the available materials, polyurethanes (PU) are widely used due to their unique balance of mechanical flexibility, chemical stability, and biocompatibility [4]. Their segmented soft- and hard-domain structure enables precise tuning of mechanical and surface properties, supporting applications ranging from catheters and stents to wound dressings and implantable sensors.

In coatings, PU provide protective barrier proper-ties while maintaining flexibility and resistance to degradation in physiological environments. Conventional PU processing typically involves organ-ic solvents, resulting in the release of volatile organic compounds and other harmful substances during production and use. To mitigate these concerns, waterborne polyurethane dispersions (PUDs) have emerged as environmentally friendly alternatives and are the focus of this work.

II. Methods and materials

For the preparation of polyurethane coatings, a commercially available polyurethane system was employed (RUCO WATERPUR 2K-seal in combination with an 80

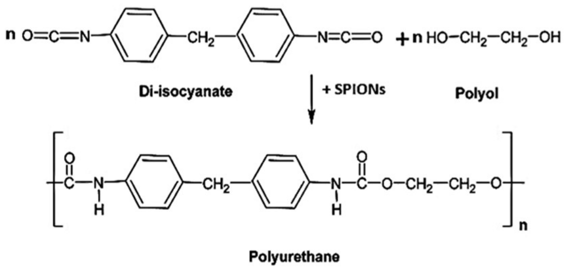

Figure 1: Synthesis of Polyurethan-SPIONs as coating.

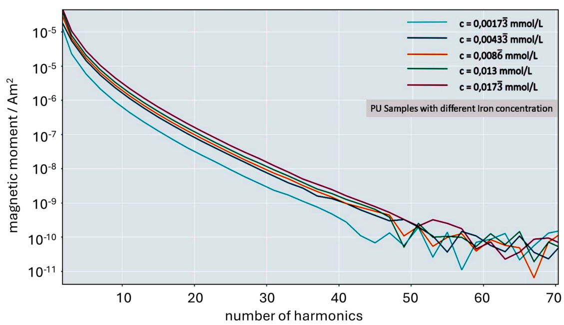

Figure 2: MPS-measurements of Polyurethan-SPION-coatings with differ-ent iron concentrations.

wt% PU hardener). The product is a two-component polyurethane (2K PUR) clear coat and sealing system, for which the specifications indicate that it can be applied to both porous, absorbent substrates and smooth substrates. Figure 1 schematically illustrates the polyurethane curing process. SPIONs with a hydrodynamic diameter of approximately 70 nm in aqueous dispersion were incorporated by continuous stirring during the polyurethane formulation process. The preparation and characterization of the nanoparticular systems can be found in [5].

This material forms a two-component system suitable for the fabrication of the coating layers. The key advantage of employing a two-component system is its straightforward and flexible processing, which does not require heat or additional reaction-initiating parameters. The nanoparticles are merely encapsulated within the coating matrix. To investigate the magnetic properties of the modified polymer, samples are measured with an in-house built MPS. The measurements were carried out under standardized conditions, i.e. a field strength of 20 mT and a frequency of 25 kHz. The detailed spectrometer system parameters can be found in [6]. MPI imaging experiments have been caried out with an in-house built field-free line system, with an excitation frequency of 25 kHz, a drive field amplitude of 20 mT, a focus field amplitude of 10 mT and a rotation of 1 s^{-1}. Image reconstruction was performed with a 1D system matrix to acquire a sinogram, which was solved with filtered backprojection.

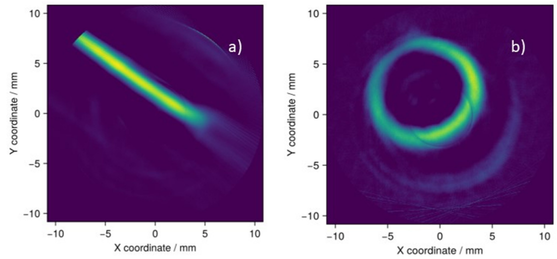

Figure 3: Results of the MPI measurement of two samples. a) Reconstruc-tion of the PU-SPION-coating on a planar surface. b) Recon-struction of the PU-SPION-coating wrapped around the sample rod as a ring.

III. Results and conclusion

The results of the MPS measurements (see Figure 2) of Polyurethan-SPION coatings with different iron concentrations, and the MPI measurements (see Figure 3) show that the SPION-PU-coating examined good signals, which enables the structural identification of the plastics after reconstruction. The incorporation into the PU matrix yielded homogeneous, elastic coatings. A water-based matrix enables homogeneous dispersion and stable integration of the particle suspension into the pre-polymer system.

MPS and MPI analyses revealed that the SPION-PU composites produced high-quality magnetic signals and allowed clear spatial mapping of their internal structure. Variations in SPION concentration and processing parameters demonstrated that both the magnetic signal intensity and polymer uniformity can be optimized through careful control of synthesis conditions. These findings confirm that the combination of SPIONs and waterborne PU offers a basis for creating magnetically detectable and mechanically robust coatings.

Author's statement

Conflict of interest: Authors state no conflict of interest.

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