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Tunable properties of magnetoactive elastomers for biomedical applications

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Abstract

The remote controllable magneto-mechanical devices based on MAEs (magnetoactive elastomers) can be obtained through variation of magnetic parameters of MAEs. Such devices can be used as the elements of peristaltic systems, artificial muscles, hyperthermia or drug delivery. MAEs with different matrix rigidity and filler particles type were investigated with VSM Lakeshore 7400 series and immittance meter Aktakom AM-3016 model. The dependencies of magnetostatic and magnetodynamic properties of MAEs with different types of magnetic particles on concentration of the magnetic filler and DC magnetic field strength were studied. There is a possibility to control the "magnetic hardness", energy absorption and heating, relaxation properties of MAEs which allow to use MAEs as the main element of the tunable devices for biomedical applications.

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Keywords: magnetoactive elastomer, tunable properties, magnetic hardness, hyperthermia, drug delivery, peristaltic system, artificial muscle;

1. Introduction

The development of "smart materials" is of high relevance nowadays due to their tunable properties (mechanical, magnetic, electrical and so on). Magnetic elastomers (or magnetorheological elastomers, or magnetoactive elastomers, or MAEs) are the unique type of smart materials. Under the applied magnetic field the changes of such properties as size, shape, Young's modulus, permittivity (Semisalova et al., 2013), permeability, energy absorption, etc. occur. The reverse effect is also possible, for example, mechanical deformations lead to magnetization changes.

The particular attention is paid to aspects of biomedical applications of MAEs (V. Q. Nguyen et al. (2012), R. Fuhrer et al. (2013)). It was found by V. Q. Nguyen et al. (2012) that MAEs have the actuation properties close to

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those of natural muscles. The magneto-mechanical properties can also be utilized in peristaltic devices like micropumps according to R. Fuhrer et al. (2013). It is known that the skeletal-muscle pumps aid in the blood circulation by venous contraction (C. F. Rothe et al. (2005) and D. Sheriff et al. (2005)). In order to demonstrate the application of magnetic particles doped silicone tubes as a magnetic pump, a magnetic peristaltic pump similar to the skeletal-muscle pump was designed and operated by R. Fuhrer et al. (2013).

The area of drugs delivery is also attractive for biomedical applications of MAEs. The principle mechanisms of the drug delivery devices are based on the fluid pumps functioning. The recent research in the drug delivery has focused on the controlling the time and amount of drug released from a reservoir. The pioneering works about control of the drug delivery with magnetic field belong to R. Langer (1990) and H. Chen et al. (1997). The deformation (caused by external magnetic field) of the MAE membrane causes a pressure change which results in the controlled drug delivery (X. Zhao et al. (2011), Y. Zhou and F. Amirouche (2011), F. N. Pirmoradi et al. (2011)).

The oncology issues, especially large tumors, can be treated by hyperthermia. The inductive heat property of magnetic elastomer composite in an alternating current (AC) magnetic field was investigated recently by L. Zhao et al. (2011). The authors showed the hyperthermia effect of the composite under the ac magnetic field. The development of the composite material for hyperthermia as a polymeric stent coating was reported by C.-Y. Kim et al. (2013).

To develop the use of MAEs in biomedical devices and applications, the certain properties of such composite materials are required. MAEs are usually based on elastic matrix and ferromagnetic particles. The variation of the matrix polymer (S. Abramchuk et al. (2007), Kallio et al. (2005)), and the type, sizes, concentration of magnetic particles (S. Bednarek (1998), N. Guskos et al. (2010), P. Siegfried et al. (2014)) leads to tunable mechanical, magnetic and electrical characteristics.

For example, the MAE combination of flexibility and tunability has attracted significant interest as soft actuators for controlled movement or positioning. The required stiffness, shape memory effect, flexibility can be provided not only by the polymer properties. Carbonyl iron microparticles have enabled the preparation of magnetic elastomers that combine the use of the highest possible saturation magnetization (pure metallic iron) and high particle loading of up to 75 wt% with respect to polymer without negatively affecting mechanical stability and integrity. The optimal particle amount for the application as soft, magnetic pump (mechanical stability and flexibility) is about 67 wt% according to R. Fuhrer et al. (2013).

It was earlier formulated by V. Q. Nguyen et al. (2012) that representative characteristics of artificial muscles include stress, strain, strain rate, bandwidth i.e., the frequency at which strain drops to half of its amplitude, work density (the amount of work generated in one actuator cycle normalized by the actuator volume), specific power, efficiency, electromechanical coupling, cycle life and elastic modulus of the material. The silicone-50 wt% Fe composite can exhibit several actuation modes (V. Q. Nguyen et al. (2012)). The dependence of saturation magnetization on the filler concentration was presented by V. Q. Nguyen et al. (2012); the saturation magnetization increased linearly with particle concentration increasing. The soft magnetic and soft mechanic elastomer with 50 wt % Fe exhibited 90 emu/g saturation magnetization and 80% elongation in magnetic field of 1 T and stronger.

Additional interest in varying of the MAE properties is an obtainment of homogeneous heat distribution under the external AC magnetic field for hyperthermia. It is of great importance to enhance the dispersion stability of particles in the matrix by heating (C.-Y. Kim et al. (2013)). The magnetic hysteresis loops, the stress-strain curves, the temperature dependences of magnetic and mechanical properties are of a great importance in the investigation of MAEs for hyperthermia. The composite film with 30 wt % of magnetite exhibits the value of saturation magnetization of 4 emu/g. The composite film showed the thermal stability up to 400◦C, about 4.4% weight loss until 408◦C (C.-Y. Kim et al. (2013)).

Sensitivity to the magnetic field is important for the description of the elastomer behavior, thus it is of particular interest to compare susceptibilities (or permeabilities) of different types of magnetic elastomers obtained by different methods. The differences between magnetic properties of the elastomers with magnetic particles and magnetic properties of the powder of the same particles can indicate the phase composition of the composite material under investigation according to P. S. Antonel (2015). The magnetic susceptibility of MAEs is the characteristic of its sensitivity to the external magnetic field. As mentioned above, the using MAEs with Fe or magnetite particles for hyperthermia processes became possible due to their heating via the absorption of AC