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EFFECT OF MAGNETIC FIELD ON ELECTRIC AND ACOUSTIC PROPERTIES OF THE PDMS FERROMAGNETIC GEL

Leszek KUBISZ(1), Andrzej SKUMIEL(2), Arkadiusz JÓZEFCZAK(2), Edward PANKOWSKI(1)

(1) University of Medical Sciences in Poznań
Department of Biophysics
A. Fredry 10, 61-701 Poznań, Poland
e-mail: kubisz@amu.edu.pl

(2) Adam Mickiewicz University
Institute of Acoustics
Umultowska 85, 61-614 Poznań, Poland

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A polymer gel (ferrogel) is an assembly of ferromagnetic nanoparticles embeded in gel. In the ferrogel, the finely distributed magnetic particles are suspended in the swelling liquid and forma flexible matrix due to adhesive forces. The present paper describes an electric and acoustic study of magnetic field sensitive poly (dimethyl siloxane) ferrogel. The results showed hysteresis of acoustic properties of the polymer gel due to variation of magnetic field. Electrical measurements showed that electric properties of ferrogel are also affected by magnetic field.

Keywords: ferromagnetic gel, magnetic field, electric properties, acoustic properties.

1. Introduction

Ferromagnetic gels belong to a group of composite materials, which are chemically cross-linked polymer networks with suspended ferromagnetic nanoparticles. Possible applications of ferromagnetic gels include electromagnetically induced hyperthermia, construction of artificial muscles, controlled drug release and many other [1–4]. The PDMS – poly (dimethyl siloxane), is the most commonly used silicon base organic polymer, inert and non toxic. It is used in contact lenses and medical devises. It is also found in elastomers, cosmetics, lubricants, dumping fluids and anti-foaming agent in food.

Iron oxide (Fe_3O_4) is a ferromagnetic substance that is chemically stable, non-toxic and non-carcinogenic. Adding it to PDMS transforms it to a magnetic stimuli responsive material. PDMS ferromagnetic gel is a suspension of ferromagnetic particle in poly (dimethyl siloxane). As a result of wide range of possible applications of PDMS ferromagnetic gel attention is paid to its electric and acoustic properties.

The mean diameter of magnetic particles suspended in the PDMS polymer matrix was determined to be equal to 8.9 nm [5]. The presence of conducting metallic particle enhances the effective electrical conductivity of the PDMS gel (2 pSm^{-1} at 20°C), which is higher than that of pure PDMS [5–7]. In the absence of an external magnetic field, magnetic gels and polymer networks show a mechanical behavior similar to that of a swollen filler loaded network. Since a typical magnetic gel can be considered as a dilute magnetic system $\phi_m < 0.1$, we may neglect the influence of magnetic interactions on the modulus. Thus the stress–strain dependence of a unidirectionally deformed gel sample can be expressed on the basis of Gaussian statistical theories [8].

Possible mechanical deformation of highly elastic PDMS after the application of magnetic uniform field [8] may lead to the modification of its electric and acoustic properties. In this paper attention is drawn to the magnetic field effects on electric and acoustic properties of the PDMS ferromagnetic gel.

2. Material

Poly(dimethyl siloxane) gel, also known as PDMS gel was used in the present study. The gel contained randomly distributed magnetite (Fe_3O_4) in the form of nanosizedparticles. The gel was a commercial product of two component reagents i.e. Elastosil 604A and Elastosil 604 B provided by Wacker Co. While the component A contained polymeric material and the Pt-containing catalyst, component B provided the cross-linking agent. Magnetite particles were synthesized by coprecipitating aqueous solution of $FeCl_2$ and $FeCl_3$ in alkaline solution [8, 9]. The particles were stabilized against agglomeration by adding 1% (w/w) of palmitic acid as a surfactant. After mixing them with the Elastosil 604 B, the cross-linking reaction had been carried out at ambient temperature for 24 hours to obtain gels. Samples of cylindrical shape and diameter of 10 mm and thickness of about 5–6 mm were prepared shortly before the experiment and placed in the measuring device.

3. Methods

Electrical measurements were carried out using a homemade cell and the HIOKI 3523-50 LCR HiTESTER. The instrument allows the simultaneous measurement of four among 14 test parameters, in the frequency range of 400 Hz–5 MHz. The assessment of the frequency dependence of selected parameters was carried out upon constant voltage of 1 V. On the basis of the recorded data electric conductivity and electric permittivity were found. To assess anisotropy of electric properties sample's axis was placed at first parallely, next perpendicularly to the magnetic induction B of the applied field.

Measurements were performed at the temperature of 21°C, in the uniform magnetic field varying from 0 to 0.5 T. The magnetic induction was measured by means of a Resonance Technology RX21 type teslameter and burden with the error $\Delta B \pm 1$ mT.

Electric properties of the PDMS ferrogel were characterised by the dielectric permittivity (ε_r) which was calculated using the relation:

$$\varepsilon_r = \frac{Cd}{\varepsilon_0 A},$$

where C is the measured value of capacitance of the sample, d is the thickness, A is the surface area, and ε_0 is the electric permittivity of air.

Changes in the ultrasound wave attenuation were measured by the pulse method using a Matec apparatus. Ultrasonic wave was generated inside the ferrogel (with length $l = 2$ cm) by a piezoelectric transducer acting as a transmitter, and received by another transducer frontally placed and aligned on the same axis. The magnetic field was generated by an electromagnet controlled by a system with a programmable current source. This allowed an automatic sweep of the range of the magnetic field studied in a given time. The measurements were performed as a function of magnetic field increasing and decreasing at a constant rate. In our experiment vector of external magnetic field **H** was perpendicular to the ultrasonic wave propagation vector **k**.

4. Results and discussion

The dispersion of dielectric permittivity was evaluated in the frequency range of 400 Hz–5 MHz. Variations of dielectric permittivity of the PDMS ferrogel sample measured inside and outside the magnetic field of 0.5 T are shown in Fig. 1. The axis of he sample was parallel to magnetic induction of the applied field, as well as to the electric field. It can be seen in the graph, that dielectric permittivity evaluated without the magnetic field decreases slightly with the frequency up to 300 kHz. Next, the dielec-

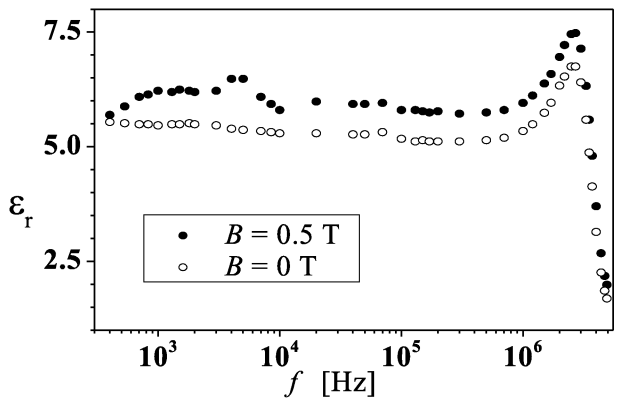

Fig. 1. Dispersion of dielectric permittivity of the PDMS ferrogel. The axis of the sample parallel to B.

tric permittivity increases revealing the maximum at the frequency of about 2.6 MHz. The dispersion determined for the sample located at uniform magnetic field – magnetic induction of 0.5 T – is more complex and reveals two local maxima at 4.5 kHz and 2.6 MHz.

Figure 2 represents the variation of dielectric permittivity of a sample, whose axis was placed perpendicularly to the uniform magnetic field and measured at the frequency of 4.2 MHz. Thus, the electric field and the magnetic field within the sample were perpendicular to each other.

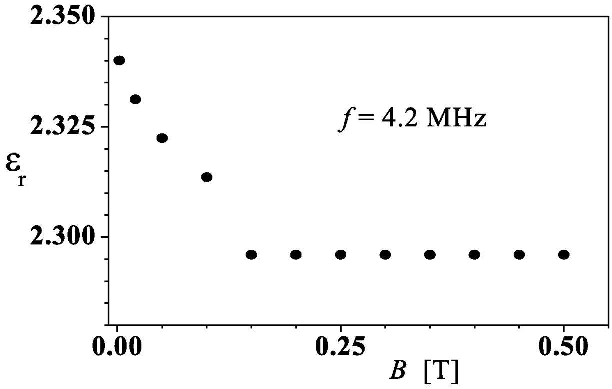

Fig. 2. Dielectric permittivity vs. magnetic induction B. The axis of the sample perpendicular to B.

Initially, the increase in the magnetic induction up to 0.15 T, caused the decrease in the dielectric permittivity. Further increase in the magnetic induction led to the stabilization of the dielectric permittivity at the value of approximately 2.29.

The results shown in Fig. 1 and Fig. 2 allow to conclude that dielectric permittivity of the PDMS ferromagnetic gel depends on the orientation of the sample in the applied magnetic field.

The experimental error of dielectric permittivity was about 2%. It is assumed that the obtained differences in dielectric permittivity are probably the result of the orientation of magnetic particles in the external magnetic field. The stabilization of the dielectric permittivity for the magnetic induction higher than 0.15 T is presumably a symptom of saturation effect.

Figure 3 shows the influence of the magnetic field on the absorption coefficient of the ultrasonic wave ($f = 1.3$ MHz) when the magnetic field increase and decreases at a constant rate. The magnetic field in the range 0–1.13 T was swept in the course of 1 minute.

The variation of the absorption with the changing magnetic field is most probably related to evolution of the internal structure of the gel caused by a rearrangement of the magnetic particles within the polymeric network. Furthermore a hysteresis is observed.

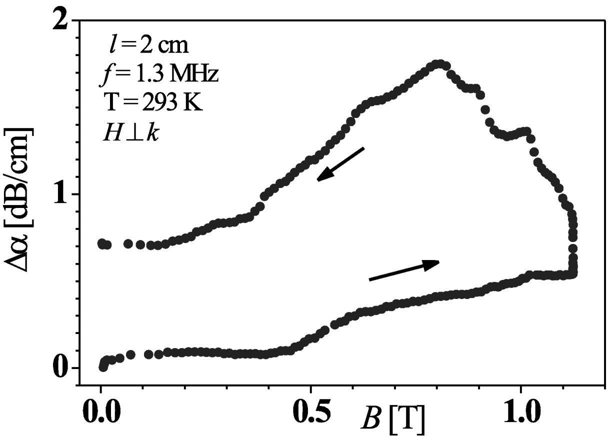

Fig. 3. Changes in the ultrasound wave attenuation versus the magnetic field strength.

5. Conclusions

The electric and acoustic properties of the PDMS ferrogel are influenced by external magnetic field.

The revealed hysteresis of the absorption coefficient of the ultrasonic wave, the dispersion and the anisotropy of the dielectric permittivity within the magnetic induction range 0–1.13 T, are presumably related to interactions between the external magnetic field and magnetite particles, which are coupled by adhesion forces to a ferrogel network.

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