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Research Paper

Mechanical and hyperthermic properties of magnetic nanocomposites for biomedical applications

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ABSTRACT

An understanding of the properties of multifunctional materials is important for the design of devices for biomedical applications. In this paper, a combination of experiments and models was used to study the mechanical and hyperthermic properties of magnetic nanoparticles (MNP)-filled PDMS composites for biomedical applications. These are studied as a function of the weight of MNP, γ-Fe_2O_3. The results showed the effects on mechanical behavior, and specific losses in a magnetic field. The measured Young's moduli are in good agreement with the moduli predicted from the Bergström–Boybce model. Specific losses calculated from magnetic measurements are used to predict the thermal dose under in-vivo conditions. The implications of the results were discussed for potential applications in biomedical devices

1. Introduction

Polydimethylsiloxane (PDMS) has attracted considerable attention in recent years due to its potential applications in biomedical engineering (Rosi and Mirkin, 2005; Brigger et al., 2002; Hergt and Dutz, 2007), biochemical engineering (Kim et al., 2010) and micro-engineering (Xia and Whitesides, 1998; McDonald and Whitesides, 2002). This is due to its attractive combinations of ease of fabrication, biocompatibility and optical transparency (Johnston et al., 2014). This attractive combination of properties makes PDMS a good candidate for the development of multifunctional composite materials.

Multifunctional nanocomposites consisting of polymer matrix and magnetic nanoparticles filler are highly sought after in the field of biomedical sciences due to their potential applications in biomedical devices for disease diagnosis

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(Rosi and Mirkin, 2005), drug delivery (Brigger et al., 2002) and thermotherapy (Hergt and Dutz, 2007). Fabrication and characterization of various nanocomposites have been previously studied and reported in the literature (Guo et al., 2007, 2008, 2014; Zhang et al., 2009; Zhu et al., 2010; He et al., 2012;). For example, Guo et al. (2013) fabricated reinforced magnetic epoxy nanocomposites with conductive polypyrrole nanocoating on nanomagnetite as a coupling agent and systematically studied the effects of the weight fraction of nanomagnetite on the rheological behavior, thermal stability, dynamic mechanical properties, mechanical properties, electrical conductivity, dielectric properties and magnetic properties.

Furthermore, silver and carbon particle-filled PDMS-based conducting composites have been examined for potential applications in the patterning of conducting structures (Liu et al., 2006; Niu et al., 2007). Kim et al. (2010) have also fabricated magnetic nanocomposite micro-heaters that are composed of Fe_3O_4 nanoparticles and PDMS. These have been considered for applications in microchips. The micro-heater has also been shown to amplify the target DNA (732 bp) with 90% efficiency compared to the conventional PCR thermocycler and also exhibit good temperature control (Kim et al., 2010).

Although such novel applications of PDMS-based multifunctional materials have shown great promise, to the best of our knowledge, there has been no fundamental research to explore the possibility of using magnetic nanoparticle-filled PDMS in the design of biomedical devices such as cell-based biochips (Prauzner-Bechcicki et al., 2014) and thermotherapy devices (Kawashita et al., 2010). Furthermore, to aid the development of such multifunctional materials for the design of novel biomedical devices for clinical use, there is a need for models that can predict their essential properties and behavior.

In this study, a combination of experiments and theoretical models was used to investigate the structural, mechanical, magnetic and hyperthermic properties of magnetic nanoparticle, γ-Fe_2O_3, reinforced PDMS. Samples with varying weight fractions (0–10 wt%) of γ-Fe_2O_3 nanoparticles were fabricated and tested at room temperature. The implications of the results were discussed for potential applications in biomedical devices.

2. Materials and method

2.1. Materials

Commercially available γ-Fe_2O_3, nanoparticles (high purity, 99.5%, 20 mm) were purchased from US Research Nanomaterials Inc, Houston, TX, USA, while polydimethylsiloxane (PDMS) Sylgard 184 silicone elastomer kit was purchased from Dow Corning Corporation, Auburn, MI, USA. These were used to prepare the nanocomposite samples.

2.2. Nanocomposite fabrication

Three types of samples, designated as PDMS-0, PDMS-5 and PDMS-10, were prepared. PDMS-0 was a γ-Fe_2O_3-free nanocomposite. It was studied as a control. The other sample names and their compositions are summarized in Table 1. A simple soft lithography technique was used to fabricate the γ-Fe_2O_3:PDMS samples.

Table 1 – Composition of the samples.

Sample	Name	ϕ_{MNP} (wt%)	
		γ-Fe_2O_3	PDMS
1	MNP-0	0	100
2	MNP-5	5	95
3	MNP-10	10	90

γ-Fe_2O_3 nano-powder was added to PDMS elastomer kit (base) and the mixtures were stirred thoroughly with a spatula for 15 min to ensure uniform distribution of the γ-Fe_2O_3 nanoparticles and also avoid clustering. Curing agent of the PDMS base was then added at a weight ratio of 10:1 and whisked vigorously with a spatula to produce a uniform mixture with adequate cross-linking. The resulting mixtures were then placed in a Vibro-deairator (Gilson Company Inc., Lewis Center, OH, USA) for 1 h. This was done to ensure that the air bubbles were completely removed. The resulting γ-Fe_2O_3:PDMS nanoparticle mixtures were poured into molds for the fabrication of tensile and compressive specimens. The tensile samples were baked at 100 °C for 43 min, while the compressive samples were baked at 100 °C for 53 min. According to Schneider et al. (2008), these curing times ensure uniform temperature distributions within the samples. After baking, the PDMS replicas were removed and peeled off.

2.3. Structural characterization

The crystal structure of the nanoparticles that were used in this study was verified using transmission electron microscopy (TEM). The microstructure of the NC samples was studied using a Quanta 200 FEG MKII scanning electron microscope (FEI, Hillsboro OR, USA). All of the samples were coated with carbon to prevent charging during scanning electron microscopy (SEM) examinations. The SEM photomicrographs were obtained for different magnifications (2 k × and 10 k ×) at an operating voltage of 10 kV.

2.4. Mechanical testing

2.4.1. Tension testing

The tensile samples were fabricated and tested in accordance with the ASTM D142-C code. The dog-bone samples were cast in an acrylic mold [See Fig. 1(a)] with a length of 57.5 mm, a width of 12.5 mm and a thickness of 3 mm. The samples were then mounted in an Instron 5567A mechanical testing machine (Instron, Norwood MA, USA) that was operated at a crosshead velocity of 254 mm min^{-1}. To ensure uniform pressure distribution across the elastomer sample, thin sheets of teflon were inserted between the samples and grips. The displacements and the corresponding forces were recorded automatically using the Bluehill 2 software program (Instron, Norwood MA, USA).

The force and displacement data were transformed into stress and strain. The stress (σ) was calculated by dividing the force by the initial cross-sectional area of the test section of the sample. The corresponding strain (ε) was calculated from the ratio of deflection (ΔL) to the initial length (L_0) of the test