Design parameters for magneto-elastic soft actuators

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2010 Smart Mater. Struct. 19 055017

(http://iopscience.iop.org/0964-1726/19/5/055017)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 155.69.4.4
The article was downloaded on 09/06/2010 at 02:56

Please note that terms and conditions apply.
Design parameters for magneto-elastic soft actuators

R L Snyder, V Q Nguyen and R V Ramanujan

School of Materials Science and Engineering, Nanyang Technological University, 639798, Singapore

Received 4 September 2009, in final form 17 February 2010 Published 31 March 2010
Online at stacks.iop.org/SMS/19/055017

Abstract
Novel soft actuators can be designed from ferrogels by combining the elastic behavior of a polymer matrix with the magnetic properties of a magnetic filler. A thorough understanding of the mechanical behavior of ferrogel actuation is essential for optimizing actuator performance. For actuation by linear magnetostriction, the influence of geometrical parameters on the onset and magnitude of hysteretic loss, the range for the continuous deformation ratio, the rate of change of the deformation ratio with respect to the field strength, and the saturation elongation were modeled. These results demonstrate that geometrical design parameters such as specimen length, aspect ratio, and distance from the magnetic field source can be used to tune the performance of ferrogels.

1. Introduction
In a ferrogel composite system, the elastic properties of a polymer matrix can be coupled with the responsive properties of a magnetic filler. This constituent property coupling results in the potential for large deformation of the entire ferrogel in an external magnetic field [1]. These materials have been studied for a wide range of technological applications, ranging from artificial tissues [1], drug carriers [2], and cancer therapeutics [3] to active clothing [4], robotics [4], damping components [5], vibration/shock absorbers [6], and stiffness tunable mounts [7]. Ferrogels can be deformed to high deformation ratios in three dimensions; they are lightweight and relatively inexpensive, and they can undergo cyclic deformation with minimal damage and release of byproducts into the environment [8]. Ferrogels also have tunable magnetic properties, which is a significant advantage over bulk magnets. Therefore, understanding their mechanical behavior is crucial to optimize their performance.

In addition to actuation, ferrogels can also be used for sensing; this dual functionality results in a ‘smart’ [9, 10] or ‘intelligent’ [11] material. By utilizing an additional dispersion of a suitable conductive filler, small changes in deformation can be correlated to large changes in electrical resistivity [12]. Therefore, the resistivity of the ferrogel can serve as a feedback mechanism for measuring the extent of deformation. Precise and real-time control of deformation is thus made possible through the ferrogel deformation ratio–electrical behavior.

The elastic response of ferrogels is governed by the mechanical properties of the polymer. In order to maximize deformation ratio, elastomers are often chosen as the matrix. Common polymers used include hydrogels [13–18], silicones [19–21], and polyurethanes [22, 23]. Magnetic particle size can also be varied, typically within the micron- or nano-scale size regimes. It is generally easier to achieve adequate interfacial adhesion with micron-sized particles due to negligible particle migration. Magnetic nanoparticles can be superparamagnetic with zero remanence [24]. Due to their small size, metallic nanoparticles tend to form an oxidative layer, reducing the electrical conductivity necessary for sensing [25]; consequently, a conductive filler material, such as graphite, is sometimes added.

The magnetic response of a ferrogel is controlled by the magnetic properties of the filler, which should have high magnetic susceptibility and saturation magnetization. Another variable is the concentration of magnetic filler [26], which influences mechanical integrity [25, 27] and responsiveness. As the concentration of magnetic material increases, so does the magnetic response. In some cases, the particles may act as cross-linking sites within the matrix and alter the elastic properties.

In a ferrogel, particles move in response to a magnetic field gradient, resulting in deformation of the composite. Equilibrium is achieved by balancing this magnetic energy with the elastic energy of the polymer. Strong adhesion between the polymer and the particles makes the system deform as a whole. If the adhesion is weak, the magnetic particles will migrate through the polymer [28]. Additionally, strong adhesion between matrix and filler eliminates Brownian rotation of the filler.
The shape transitions that occur in ferrogels in the presence of a magnetic field and the influence of both uniform [7, 20, 29] and non-uniform magnetic fields [30, 31] on actuation behavior have been previously examined. The dynamic behavior of polymer systems has been generalized [32] to include terms relevant to these composites, and neutron-spin-echo spectrometry has been used to study magnetic particle behavior within the polymer matrix [33]. The synthesis and performance of anisotropic gels [27, 34, 35], the effects of matrix material, magnetic filler concentration, and magnetic field strength [2, 6] on composite performance have been previously documented. The mode and mechanism of deformation [2] as well as the saturation [36] and hysteric-type deformation ratio [37] behavior have been studied.

Previous work on ferrogels has focused on the effects of the above intrinsic variables on ferrogel performance. Variables commonly studied include the type of polymer and magnetic filler, magnetic filler concentration, and strength of the external magnetic field [2]. In contrast, this work focuses on how specimen geometry can be used to alter the performance and efficiency of ferrogel systems.

For the elongation of cylindrical ferrogel specimens, the geometric configuration of a ferrogel has a significant impact on performance and efficiency. Key parameters include specimen length, aspect ratio, and relative distance from the field source. Geometric effects are important due to the limiting interplay between the magnitude of reasonably achievable magnetic fields and specimen size.

Modes of deformation of the ferrogel include elongation [17], deflection [38], contraction [39], and coiling [40]; this study focuses primarily on elongation. This study shows that geometrical parameters can have a significant impact on the performance and behavior of the ferrogel. It is also demonstrated that for a given specimen length, there is an aspect ratio which will maximize energy density and work that can be performed. To our knowledge, this is the first such study of the effect of specimen geometry on actuation behavior of ferrogels. These results are most directly related to applications in which a cylindrical ferrogel specimen is actuated by a magnetic field source; however, the model developed here can be readily extended to configurations and magnetic sources.

2. Results and discussion

2.1. General characteristics of ferrogel deformation

In the case of elongation, cylindrical ferrogels demonstrate an interesting deformation ratio–field behavior when exposed to a non-uniform magnetic field generated by an electromagnet [2, 31]. The deformation ratio is the deformed specimen length divided by the original length. Figure 1 shows a typical deformation ratio (λ) versus magnetic field (B_{max}) plot for a ferrogel, for which B_{max} is the magnetic field at the center of the electromagnet poles. The graph can be divided into the following regimes: for small magnetic fields (region (a)) deformation will be continuous and gradual. Next, at some critical magnetic field (region (b)), the system undergoes a large scale mechanical transition corresponding to a discontinuous change in deformation ratio. After this transition, the system again undergoes gradual, continuous deformation (region (c)), followed by saturation of elongation behavior (region (d)). Ferrogels can also exhibit a deformation ratio–relaxation hysteretic response (region (e)).

The effects of specimen geometry on the maximum achievable deformation ratio, or saturation elongation (λ_s), and the corresponding magnetic field (B_s), the field value at the onset of the mechanical transition (B_{mag}), the maximum deformation ratio of the initial continuous regime (λ_c), deformation ratio achieved due to the mechanical transition (λ_d), and the width of the hysteresis loop (w_h) were evaluated using the energy model described below.

2.2. Energetics

The linear magnetostrictive deformation ratio of cylindrical specimens in the presence of the magnetic field generated by an electromagnet was studied (figure 2). One end of a specimen, with initial length h_o, was fixed at a distance z_o from the centerline of the electromagnet dipoles while the other end was free to respond to the magnetic field. The change of free energy in the presence of an external magnetic field is used to model the deformation ratio–field behavior [2].

The deformation ratio was calculated as a function of the magnetic field strength for various specimen configurations. The Helmholtz free energy (A_t, equation (1)) of the composite is the sum of two terms: the elastic energy (A_{el}, equation (2)) and magnetic energy (A_{mag}, equation (3)). G_P is the shear modulus of the polymer matrix, V is the specimen volume, and λ_s is the deformation ratio as a function of z, the distance of the point of interest from the center of the electromagnet poles. Constant volume is assumed. The Poisson’s ratio of

![Figure 1](image-url)
rubber-like materials is nearly equal to 0.5 \cite{41}; therefore, this is a reasonable approximation. Wolfram’s Mathematica 6 Student Edition computational software was used to complete all calculations.

$$A_t = A_{el} + A_{mag}$$  \hspace{1em} (1)

$$A_{el} = \frac{1}{2} G_{p} V \left( \lambda_{e}^{2} + \frac{2}{\lambda_{e}} - 3 \right)$$  \hspace{1em} (2)

$$A_{mag} = -\frac{\chi d_{o}}{2 \mu_{o} \lambda_{e}} \int_{z_{o} - \delta}^{z_{o}} B^{2}(z) \, dz.$$  \hspace{1em} (3)

In these equations, $\chi$ is the magnetic susceptibility of the ferrogel, $d_{o}$ is the initial cross-sectional area of the specimen, $\mu_{o}$ is the permeability of free space, and $B(z)$ is the magnetic field strength as a function of $z$.

Zrinyi et al suggested that the relationship between field decay ($k$) and electromagnet pole radius ($\delta$) is given by $k = \gamma/(2\delta + \gamma \delta^{2})$, where $\gamma$ is a constant, characteristic of the electromagnet \cite{2}. Using this expression, the magnetic field strength as a function of $z$ can be determined (figure 3) for various $B_{max}$ values ($B_{max}$ is set by the maximum current through the electromagnet windings) using equations (4)–(6).

$$B(z) = B_{max} f(z)$$  \hspace{1em} (4)

$$f(z) = 1 - k \lambda_{e}^{2} \quad \text{if } |z| < \delta$$  \hspace{1em} (5)

and

$$f(z) = (1 - k \delta^{2}) \exp[-\gamma(|z| - \delta)] \quad \text{if } |z| \geq \delta.$$  \hspace{1em} (6)

The equilibrium deformation ratio for a given magnetic field strength was determined by identifying the minimum energy value. This value was then paired with the $B_{max}$ value of the associated magnetic field to generate the deformation ratio–field curves. Key parameters of interest include $d_{o}$, $h_{o}$, $z_{o}$, $B_{max}$, specimen aspect ratio, and $V$. Unless otherwise noted, all calculations used values of shear modulus $G_{p}$ of 60000 Pa, dipole radius $\delta$ of 0.015 m, field intensity $\gamma$ of 40, filler concentration $\Phi_{m}$ of 0.02, and magnetic susceptibility $\chi = 21.2 \Phi_{m}$.

A crucial aspect of the energy terms is their differing dependence on specimen geometry. The elastic energy is dependent on the specimen volume whereas the magnetic term is proportional to the cross-sectional area of the specimen integrated over its length. This key difference suggests that the specimen geometry and configuration ($d_{o}$, $h_{o}$, $z_{o}$, aspect ratio) can be altered to tune performance parameters. The effect of initial cross-sectional area ($d_{o}$), initial length ($h_{o}$), distance from the field source ($z_{o}$), specimen aspect ratio (AR), and specimen volume ($V$) were studied.

Original specimen lengths ($h_{o}$) ranging from 1 mm to 30 cm were considered. Aspect ratio (AR, equal to original length divided by original diameter) ranging from 1 to 7, and specimen distance from the field source ranging from 1.5 to 2 times that of the original specimen length were studied. An initial distance of 1.5 times that of the specimen length implies that the closest end of the specimen is at a distance from the center of the electromagnet poles of 0.5 times its initial length. A constant volume study was also conducted.

2.3. Effect of polymer modulus and filler concentration

The effects of polymer modulus ($G_{p}$) and volume concentration of magnetic component ($\Phi_{m}$) were studied (figure 4). Similar to previous work \cite{2}, increasing the polymer modulus resulted in a small decrease in $\lambda_{e}$ and an increase in $B_{act}$. A large increase in $B_{act}$ from 0.1 to 0.5 T was observed (figure 4(a)). An increase in filler concentration from 0.01 to 0.05 significantly decreased $w_{th}$, slightly increased $\lambda_{e}$, and decreased $B_{act}$ from 0.2 to 0.1 T (figure 4(b)).

2.4. Geometrical effects: aspect ratio, specimen length, and distance from the field source

Increasing the distance of the specimen from the field source (figure 5(a)) from 4 to 6 cm resulted in an increase of $\lambda_{d}$ and $\lambda_{i}$ values, as well as an increase in $B_{act}$ from 0.1 to 0.2 T. These results are similar to those of previous work \cite{2}.

Altering the specimen geometry can have significant effects on ferrogel deformation. An increase in aspect ratio from 3 to 5 (for $h_{o}$ of 9 cm, figure 5(b)) decreased $B_{act}$ from 0.5 to 0.25 T. An increase in the slope of the $\lambda$ versus $B_{max}$ curve at the mechanical transition (denoted by $m_{g}$) was also observed for small specimen lengths due to a change from continuous to discontinuous deformation. Aspect ratio has these effects for both constant volume and constant initial
Figure 4. Deformation ratio–relaxation profiles studied for various values of (a) polymer shear modulus $G_p$ and (b) magnetic particle concentration $\Phi_m$, all other variables held constant.

Figure 5. Deformation ratio–relaxation profile for various (a) distances from the field source $z_o$, (b) specimen lengths $h_o$, and aspect ratios.

length conditions. Figure 6 is a plot of deformation as a function of magnetic field for specimens possessing the same volume (5.5 cm$^3$) but different aspect ratios, of 3 (figure 6(a)) and 7 (figure 6(b)), respectively. Although the specimen volumes are identical, the deformation profiles are significantly different. The slope of the deformation versus field curve of the specimen with aspect ratio equal to 3 (figure 6(a)) is much less than the corresponding curve for the larger aspect ratio.
Figure 6. Deformation ratio–relaxation profiles for specimens of equal volume but varying geometries: (a) initial diameter of \((7/3)^{1/3}\) cm and aspect ratio of 3 and (b) initial diameter of 1 cm and aspect ratio of 7.

specimen (figure 6(b)), demonstrating that aspect ratio can be used to change the specimen response. Similar effects can be observed when specimen length is constant and aspect ratio is changed. Figure 7 is a graph of deformation as a function of magnetic field for two specimens of the same original length (3 cm) and aspect ratios equal to 1 (figure 7(a)) and 7 (figure 7(b)), respectively. Changes to the aspect ratio results in significant differences in the slope of the \(\lambda\) versus \(B_{\text{max}}\) curve at the mechanical transition.

An increase in initial specimen length (figure 5(b)) elicits a ‘peak behavior’ in \(\lambda_c\). ‘Peak behavior’ refers to an initial increase in achievable deformation, which reaches a maximum and is followed by a subsequent decrease in value corresponding to increasing specimen lengths. For example, at an aspect ratio of 3, increasing the initial length from 7 to 9 cm increased the \(\lambda_c\) from 1.05 to 1.15; however, further increase in length from 9 to 15 cm resulted in a decrease in \(\lambda_c\) from 1.15 back to 1.05. Similarly, for an aspect ratio of 5, increasing specimen length from 9 to 15 cm decreased \(\lambda_c\) from 1.78 to 1.7. \(B_{\text{act}}\) also increased from 0.25 to 0.9 T (figure 5(b)).

As noted above, for a given specimen length, it is observed that specific aspect ratios of the specimen yield greater saturation elongation values. This phenomenon was used to compare the difference in efficiency of ferrogels that results from various geometric parameters. The energy density (\(\rho E\)) was used to calculate the work (\(W\)) that can be performed by the ferrogel actuators [2] of a given volume (equations (7) and (8)).

\[
W = m_1 (\lambda - 1) h_o \tag{7}
\]

\[
\rho E = \frac{W}{V} \tag{8}
\]

For a given specimen volume, the work that can be performed by lifting a mass during relaxation from saturation elongation was calculated. This work was correlated with the specimen volume to calculate energy density as a function of initial specimen length (\(h_o\)), aspect ratio (AR), and distance from the field source (\(z\)). The maximum mass (\(m_l\)) that can be lifted by the specimen, with the specimen deforming by a maximum of 5%, was used for these calculations (equation (9)). \(Y_P\) is the Young’s Modulus of the polymer.

\[
m_l = \left(0.05 \right) V Y_P \left(\frac{g h_o (1.05)}{2} \right). \tag{9}
\]

Increasing the distance from the field source from 1.5\(h_o\) to 2.0\(h_o\) resulted in a significant increase in energy density. Figure 8 is a plot of specimen energy density as a function of
Figure 8. Energy density based on aspect ratio AR, distance from field source \(z\), and initial specimen length. (This figure is in colour only in the electronic version)

Table 1. Results indicating performance parameters as a function of increasing aspect ratio, initial specimen length, and distance from the field source.

<table>
<thead>
<tr>
<th>Effect on actuator characteristics</th>
<th>Increasing magnitude of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aspect ratio</td>
</tr>
<tr>
<td>(\lambda_c)</td>
<td>pk</td>
</tr>
<tr>
<td>(\lambda_d)</td>
<td>0</td>
</tr>
<tr>
<td>(\lambda_f)</td>
<td>+</td>
</tr>
<tr>
<td>(B_{act})</td>
<td>--</td>
</tr>
<tr>
<td>(B_t)</td>
<td>--</td>
</tr>
<tr>
<td>(m_d)</td>
<td>++</td>
</tr>
<tr>
<td>(w_h)</td>
<td>pk</td>
</tr>
</tbody>
</table>

Symbol Meaning

0 No influence
+ Negligible increase
++ Significant increase
-- Significant decrease
pk Peak-like response (initial increase followed by decrease)
3. Conclusions

The mechanical behavior of ferrogel specimens was modeled for a wide range of geometrical parameters; these results can be used to optimize the actuation behavior of ferrogels.

The following conclusions were reached.

- Geometrical parameters, such as aspect ratio, length of specimen, and distance from the field source can have a significant impact on the performance and efficiency of the ferrogel.
  - Increasing the distance from the magnetic field source increased deformation ratio achieved via the mechanical transition, saturation elongation, and the corresponding magnetic field values.
  - An increase in initial specimen length increased deformation ratio obtainable in the initial, continuous deformation regime, as well as the deformation ratio immediately following the discontinuous transition and the saturation elongation. The magnetic field strengths required to elicit the mechanical transition and to reach saturation elongation also increased.
  - Increasing the aspect ratio decreased the deformation ratio obtainable within the initial, continuous regime, decreased the field strength needed to obtain saturation elongation, increased the slope of the $\lambda$ versus $B$ curve at the mechanical transition, and decreased the saturation elongation value.
- For a given specimen length, there is an aspect ratio which will maximize the energy density and work that can be performed by the specimen.

Acknowledgments

The authors thank the Asian Office of Aerospace Research and Development, Tokyo, for financial support through grant AOARD-08-4120. R Snyder performed this work under a grant provided by the Fullbright Program of IIIE, funded by the Department of State, USA.

References

[1] Chen J, Zhang G X and Jin J 2007 Preparation and deflection characterization of intelligent polymer gels controlled by magnetic fields ROBIO: 2007 IEEE Int. Conf. on Robotics and Biomimetics (Sanya)
[10] Zrinyi M 2002 Electrical and magnetic field-sensitive smart polymer gels Polymer Gels and Networks ed Y Osada and A R Khokhlov (New York: Dekker) p 381
[14] Furher R et al 2009 Crosslinking metal nanoparticles into the polymer backbone of hydrogels enables preparation of soft, magnetic field-driven actuators with muscle-like flexibility Small 5 383–8 (Weinheim an der Bergstrasse, Germany)


[34] Varga Z, Filipcei G and Zrínyi M 2005 Smart composites with controlled anisotropy Polymer 46 7779–87


[38] Ramanujan R V and Lao L L 2006 The mechanical behavior of smart magnet–hydrogel composites Smart Mater. Struct. 15 952–6

