Quasi-unidirectional shrinkage of gels with well-oriented lipid bilayers upon uniaxial stretching†

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PDGI–PAAm gels with well oriented lipid bilayers show a quasi-unidirectional shrinkage upon uniaxial stretching along the bilayers. They shrink largely parallel to the bilayer but slightly perpendicular to it in order not to increase the bilayer area and its interfacial energy. Such an anisotropic deformation can be well-modelled based on classical theories for gel networks and lipid layers.

Generally, gels have an isotropic network structure and show an isotropic deformation as shown in Fig. 1(a). One of the typical examples is free swelling. When isotropic gels are immersed in solvents, the deformation (swelling) ratio of each direction α is ideally same. Another example is uniaxial stretching experiment. Note that gels’ Poisson’s ratio is very close to 0.5 if solvent exchange is not accompanied by deformation.1 When gels are uniaxially stretched along the x-axis with the deformation ratio of 0.5, they similarly shrink along the y and z-axes with the deformation ratio of 0.5. On the other hand, if any restriction is introduced to the gels, the deformation of such gels does not follow the formulas of isotropic gels.2–5 For example, when a hydrogel having a liquid crystalline structure is put under a magnetic field, the orientation of the liquid crystal induces an anisotropic swelling of the gel.2 A spherical gel surrounding a hard core shows a water content distribution at the equilibrium state due to the swelling constraint near the core.3 If a gel with a patterned cross-linking distribution swells, many bumps are formed on its surface due to the swelling degree distribution.4 One kind of gel having such restrictions, the PDGI–PAAm gel with thousands of monodomain lamellar bilayers, has been reported.6–9 This gel consists of hard, uniaxially-oriented sheet-like poly(dodecyl glycidyl itaconate) (PDGI) lipid bilayers fixed within soft PAAm gel as the matrix. The structure of a PDGI–PAAm gel is shown in Fig. 1(b). The monodomain PDGI bilayer structure is realized by applying a strong shear when the gel precursor solution is poured into a mould.6 This gel shows brilliant structural colour due to its well-oriented and periodic lamellar structure. This colour can be modulated by external stimuli such as mechanical force,6,8 pH and temperature.9

One of the most remarkable behaviours of a PDGI–PAAm gel is unidirectional swelling, shown in Fig. 1(b).6 When the PDGI–PAAm gel with an oriented PDGI bilayer in the x–y plane is swollen in water, this gel swells only along the z-axis, which is perpendicular to the bilayer plain. Such unidirectional swelling of gels with a layered structure has been also reported by Kang et al.10 This strange phenomenon is because increasing the area

Fig. 1 (a) Size change of an isotropic gel upon swelling and uniaxial stretching. (b) The structural model and unidirectional swelling behaviour of a PDGI–PAAm gel with hard monodomain lipid bilayers in the soft gel matrix.
of the bilayer is energetically unfavourable. The amorphous PAAm gel layers tend to keep their “shape” during swelling as explained above, whereas lipid bilayers tend to keep their “area” upon deformation to maintain a low surface energy. If a PDGI–PAAm gel swells along the x or y-axes, this process is always accompanied by an area expansion of the bilayer, which is energetically unfavourable. As a result, a PDGI–PAAm gel tends to swell only along the z-axis. More precisely, Wang and Hong have proposed a simple theoretical model to explain this anisotropic swelling of PDGI–PAAm gels.11

As such anisotropic PDGI–PAAm gels show anisotropic swelling due to the bilayers, they also should show anisotropic deformation upon uniaxial stretching. Although this prediction is interesting from the physical point of view, no study for this subject has been reported. Thus, the aim of this study is to investigate how PDGI–PAAm gels deform anisotropically upon uniaxial stretching. In this paper, we investigate the deformation behaviour of PDGI–PAAm gels upon uniaxial stretching by experiments first, then we establish the theoretical model to explain these experimental phenomena.

For the sample, a monodomain PDGI–PAAm gel was prepared as reported previously.8 Briefly, 0.1 M of dodecyl glycidyl itaconate as the polymerizable lipid, 2.5 mM of sodium dodecyl sulfate (SDS) as the additive, 2 M of acrylamide as the monomer, 0.1 mol% of N,N'-methylene(bis)acylamide as the cross-linker and 0.1 mol% of IRGACURE 2959 as the initiator were added to pure water and gently mixed at 55 °C for 3 hours. The glass mould was prepared from two glass plates (thickness = 3 mm) separated by a silicone rubber spacer (thickness = 0.5 mm). The length and width of the space in the mould were 90 mm and 20 mm, respectively. Then the solution was poured into the glass mould under strong shear. Polymerization of PDGI and PAAm was then immediately carried out by irradiation with a 365 nm UV light for 3 d to remove any residual chemicals.

Here, we chose the water swelling state (just before stretching) as the reference state of gels, and defined \( \lambda_i \) (i = x, y or z) as the deformation ratio of the reference gels along the x, y and z-axes caused by uniaxial stretching. Both sides of the gel samples were fixed by two clips and uniaxially stretched along the x-axis slowly by hand to several desired deformation ratios, \( \lambda_x \). Here, it should be noted that the following measurements of \( \lambda_y \) and \( \lambda_z \) have been done after waiting for more than 90 s until complete relaxation (see Fig. S1 of the ESI† for stress relaxation tests). \( \lambda_y \) was determined by direct measurement of the gel width analysed from the pictures of the deformed gels shown in Fig. 2(a). \( \lambda_z \) was determined by reflection spectrum measurements of the gels with a Hamamatsu Photonics KK, C10027 device.4,4 The distance of two adjacent lamellar sheets, \( d \), for each \( \lambda_y \) was calculated from the peak wavelength of the reflection spectra by using Bragg’s law (concept for the measurement and raw spectra are shown in Fig. 2(b) and (c), respectively). As a change of \( d \) should be proportional to a change of gel thickness along the z-axis, \( \lambda_z \) can be calculated as \( \lambda_z = \frac{d}{d_0} \), where \( d_0 \) is \( d \) in the reference state. At any \( \lambda_z \), the calculated change of gel volume \( \lambda_x \lambda_y \lambda_z \) is almost 1, which verifies the accuracy of our measurements of \( \lambda_y \) and \( \lambda_z \) (see Fig. S2 of the ESI†).

Fig. 3(a) shows the changes of \( \lambda_y \) and \( \lambda_z \) of the uniaxially-stretched PDGI–PAAm gel upon changing the deformation ratio along the x-axis, \( \lambda_x \). The anisotropic PDGI–PAAm gel did not follow the formula for determining \( \lambda_x \), \( \lambda_y \) can be indirectly determined from the layer distance, \( d \), which can be measured by the reflection spectra with Bragg’s law. (c) Reflection spectra of the deformed gels with several \( \lambda_x \) values. In this experiment \( \theta \) was 60°.
unidirectional shrinkage has been also reported by Finkelmann and Nishikawa using a monodomain thermotropic liquid crystal (LC) elastomer.\textsuperscript{12} As their elastomer has modulus anisotropy, it mainly shrinks along the soft direction when stretched uniaxially. Our system, which can be called a mono-domain lyotropic LC gel having modulus anisotropy, seems to show a similar shrinkage to Finkelmann’s system. However, surprisingly, our gel shrinks along the ‘hard’ direction, which is the opposite to their system.

To understand the reason for the unidirectional shrinkage and the difference in shrinking direction of PDGI–PAAm gels, we studied the changes of the PDGI bilayer area. This is because not the uniaxial deformation ratio but the area expansion ratio is considered. As a result, we obtain the mixing term and elastic term of the network.

For PDGI bilayers, respectively. For \(D_{\text{el,d}}\) we consulted elastic lipid membranes. According to the literature,\textsuperscript{14} the Helmholtz free energy change per single lipid molecule upon membrane extension, \(\Delta \mu (J)\), can be roughly estimated as:

\[
\Delta \mu = \frac{\gamma (a - a_0)^2}{a_0}
\]  

where \(\gamma (\text{N m}^{-1})\) is the interfacial tension, \(a (\text{m}^2)\) is the interfacial area occupied by a single lipid molecule and \(a_0\) is \(a\) in the initial state, which should be the optimum interfacial area. Under the assumption that the area expansion ratio of a whole membrane \(\lambda_\lambda\lambda_\gamma\) is equal to that of each single molecule \(a/a_0\), eqn \(3\) can be rewritten as:

\[
\Delta \mu = \frac{\gamma}{\lambda_\lambda\lambda_\gamma} a_0 (\lambda_\lambda\lambda_\gamma - 1)^2.
\]  

A single PDGI bilayer sheet having a unit surface area at the initial state consists of 2/\(a_0\) PDGI molecules (the coefficient 2 is because of the ‘bi’-layer). Also, the volume of a single PDGI bilayer sheet with unit surface area is \(1 \times 1 \times d_{\text{dgi}}\). Hence, \(\Delta F_{\text{el,d}} (\text{J m}^{-3})\), which is the free energy change of the PDGI bilayers per unit volume of the PDGI–PAAm gel, can be calculated as:

\[
\Delta F_{\text{el,d}} = \Delta \mu \frac{2}{a_0} \frac{1}{d_{\text{dgi}}} \times d_{\text{dgi}} \frac{d_0}{d_0} = \frac{2\gamma}{\lambda_\lambda\lambda_\gamma} a_0 (\lambda_\lambda\lambda_\gamma - 1)^2.
\]  

The \(d_{\text{dgi}}/d_0\) in the second term indicates the volume fraction of the PDGI bilayers in the PDGI–PAAm gel. By substituting eqn \(2\) and eqn \(5\) into eqn \(1\) and using the relationship \(\lambda_\lambda\lambda_\gamma\lambda_\lambda\lambda_\gamma = 1\), we finally obtain:

\[
\Delta F_{\text{total}} = \frac{E_{\text{gel}}}{6d_0} \left( \lambda_\lambda^2 + \lambda_\gamma^2 + (\alpha' \lambda_\gamma)^2 - (2 + \alpha') \right) (d_0 - d_{\text{dgi}}) (d_0 - d_{\text{dgi}}) + \frac{2\gamma}{\lambda_\lambda\lambda_\gamma a_0} (\lambda_\lambda\lambda_\gamma - 1)^2.
\]  

Using the experimental parameters \(d_0 = 251\ \text{nm}, d_{\text{dgi}} = 4.7\ \text{nm}, \alpha' = 2.1\) and \(E_{\text{gel}} = 0.01\ \text{MPa}\) (roughly estimated from the compression test shown in ref. 6), we calculated the \(\lambda_\gamma\) which gives the lowest \(\Delta F_{\text{total}}\) for various \(\lambda_\lambda\) values using a numerical calculation technique with \(\gamma\) as the fitting parameter. Fig. 4 shows the fitting results of the \(\lambda_\lambda\lambda_\gamma\lambda_\lambda\lambda_\gamma\) dependence on \(\lambda_\gamma\). If \(\gamma = 10.0\ \text{mN m}^{-1}\) was used, the fitting lines almost overlapped with the experimental results. This value of \(\gamma\) is comparable to the reported values of \(\gamma \approx 10-100\ \text{mN m}^{-1}\) for some synthetic or natural lipid membranes.\textsuperscript{13,14} These facts confirm the adequacy of our simple theory.
Finally, we should comment on the difference between the results of this work and our previous work. In our previous work, we have shown uniaxial deformation-induced colour changes. The reason for this difference is probably that in the previous work we measured the reflection spectra before relaxation, whereas in this work we did it after relaxation. We have confirmed that the colour of the gel changes upon fast uniaxial deformation, while it slightly changes upon slow deformation.

In conclusion, we have found a quasi-unidirectional shrinkage of the PDGI–PAAm gels with well-oriented lipid bilayers. When they are stretched parallel to the bilayer, they tend to deform along the direction perpendicular to it without increasing the bilayer area. A simple theoretical model based on the elasticity of the gel network and lipid layer can well explain such an anisotropic deformation. In the future, the design and creation of novel lipid layer-gel composites showing unique and anisotropic deformations based on this theory are expected. Such materials could possibly be applied to artificial muscles with unique motions.

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