VISCOELASTIC CHARACTERIZATION OF SOFT MICROPILLARS FOR CELLULAR MECHANICS STUDY

I-Kuan Lin¹, Yen-Ming Liao², Kuo-Shen Chen², and Xin Zhang¹

¹ Boston University, Boston, MA 02215, USA
² National Cheng Kung University, Tainan, 701, Taiwan

ABSTRACT

The mechanical properties of polydimethylsiloxane (PDMS) were characterized by using uniaxial compression and dynamic mechanical analysis (DMA) as well as finite element simulation methods. A five-parameter linear solid model was used to emulate the mechanical behavior of PDMS. The study results indicated that the effect of viscoelasticity affected the PDMS micropillar arrays significantly. The conventional approach for calculating the cellular force basing on the linear elastic mechanics could result in considerable errors.

KEYWORDS: Polydimethylsiloxane, Viscoelasticity, and Cellular Force

INTRODUCTION

The mechanical interaction force between cells and their neighboring extracellular matrix is believed to be very important in various physiological processes. Researchers have constructed PDMS micropillar arrays as extracellular matrices and the interaction forces can be characterized by converting the measured deflection of PDMS micropillars, showing in Figure 1, using elastic mechanics of materials, where the elastic modulus of PDMS was assumed to be a constant [1]. However, PDMS is a viscoelastic material and its elastic modulus changes with loading frequencies and elapsed time durations [2]. Therefore, it is important to develop a more accurate deflection to load conversion by performing a detail material characterization on PDMS materials for biological applications. This paper reports PDMS specimen fabrication, material and mechanical characterization in both macro and micro scales, and the corresponding finite element analyses (FEA).

![Figure 1: A SEM image of a smooth muscle cell cultured on a PDMS pillar array.](image)
SPECIMEN FABRICATION AND EXPERIMENTS FOR PDMS VISCOELASTICITY BEHAVIOR

PDMS specimens in form of bulk was fabricated for Punch test and DMA characterization. On the other hand, PDMS micropillar arrays were also prepared by following the fabrication process. In order to form two types of PDMS sample, we used 30mm × 30mm × 3mm metallic molds and patterned 40μm thick SU-8 photoresist molds with 20×20 (μm²) holes. These PDMS samples were obtained by mixing PDMS prepolymer (Sylgard 184, Dow Corning) and a curing agent in a ratio of 10:1. The mixed PDMS prepolymer was poured on the three different molds and then put into a vacuum chamber for 5 minutes to remove the residual air bubbles in the film. Finally, the sample was baked at 65 ºC for 90 minutes for the purpose of curing. After separately removing the PDMS and mold, these PDMS samples were completed.

The bulk PDMS specimens have been characterized to establish the material constitutive law by using a self-developed DMA system and a punch testing system. By utilizing the punch equation developed in contact mechanics, the plane strain elastic modulus, E*, can be obtained as 1.45 MPa. Since PDMS is inherently a viscoelastic material, a stress relaxation scheme based on the same punch test was also performed. The test data and the finite element simulation (using ABAQUS v.6.4) result by using a five-parameter linear solid model are all shown in Figure 2(a). By using the Prony series approach, the viscoelastic behavior at RT of the PDMS can be modeled as

\[ G(t) = 0.455(1 - [0.08(1 - e^{-t/0.165}) + 0.03(1 - e^{-t/5})]) \]  \hspace{1cm} (MPa)

where G(t) is the shear modulus. Since the Poisson’s ratio of polymer can be reasonably assumed to be approximately 0.5, the Young’s modulus E(t) is therefore three times of G(t). The obtained viscoelasticity constitutive law would then be used for simulating the experimental data obtained by the micropillar bending test. Next, a more comprehensive study on the PDMS viscoelasticity was also performed using a self-developed DMA system. The test data and the finite element simulated results (using the frequency domain viscoelasticity model presented in Eq.(1) are both shown in Figure 2(b). The results indicated that the simulation results essentially agree with the test data.

![Figure 2: The test/simulation results of PDMS (a) stress relaxation and (b) DMA frequency domain tests.](image-url)
BENDING BEHAVIOR OF PDMS PILLARS

The obtained viscoelasticity model was then validated via micropillar bending test using a Hystron nanoindenter. In parallel, a finite element simulation model was constructed to emulate the bending process by incorporating the material behavior of the PDMS obtained from the previous test. Figure 3 shows a bending test on the PDMS micropillars using the nanoindenter with different loading rates, in conjunction with the simulation results of a 2D FEA model. It can be observed that the tendencies of two sets of data essentially agree to each other and this further validates the accuracy of the viscoelasticity model for the PDMS material. Finally, based on the model prediction shown in Figure 4 using different material models, one can see that there are considerable differences exist between different models.

CONCLUSIONS

In cellular force research, it is often assumed that the PDMS micropillar is an elastic beam with a constant Young’s modulus. However, such a conversion could be questionable due to the inherent viscoelasticity (and hyperelasticity) of PDMS. In this paper, we presented general characterization procedures and preliminary results which could provide a more accurate conversion model for related applications such as cellular force measurements.

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