DUROMETER HARDNESS AND THE STRESS-STRAIN BEHAVIOR OF ELASTOMERIC MATERIALS

H. J. Qi, K. Joyce, M. C. Boyce*

Department of Mechanical Engineering
Massachusetts Institute of Technology, Cambridge, MA 02139

ABSTRACT

The Durometer hardness test is one of the most commonly used measurements to qualitatively assess and compare the mechanical behavior of elastomeric and elastomeric-like materials. This paper presents nonlinear finite element simulations of hardness tests which act to provide a mapping of measured Durometer Shore A and D values to the stress-strain behavior of elastomers. In the simulations, the nonlinear stress-strain behavior of the elastomers is first represented using the Gaussian (neo-Hookean) constitutive model. The predictive capability of the simulations is verified by comparison of calculated conversions of Shore A to Shore D values with the guideline conversion chart in ASTM D2240. The simulation results are then used to determine the relationship between the neo-Hookean elastic modulus and Shore A and Shore D values.

The simulation results show the elastomer to undergo locally large deformations during hardness testing. In order to assess the potential role of the limiting extensibility of the elastomer on the hardness measurement, simulations are conducted where the elastomer is represented by the non-Gaussian Arruda-Boyce constitutive model. The limiting extensibility is found to predict a higher hardness value for a material with a given initial modulus. This effect is pronounced as the limiting extensibility decreases to less than 5 and eliminates the one-to-one mapping of hardness to modulus. However, the durometer hardness test still can be used as a reasonable approximation of the initial neo-Hookean modulus unless the limiting extensibility is known to be small as is the case in many materials, such as some elastomers and most soft biological tissues.

INTRODUCTION

Durometer (Shore) hardness[1] is one of the most commonly used hardness tests for elastomeric materials. Durometer hardness measurements, which assess the material resistance to indentation, are widely used in the elastomer industry for quality control and for quick and simple mechanical property evaluation.[1] The hardness value is primarily a function of the elastic behavior of the material. The nondestructive and relatively portable nature of the test enables property evaluation directly on elastomeric products or components. This feature has also led to the use of hardness tests in mechanical property evaluation of soft tissues such as skin[3-4] and tumors surrounded by soft tissues.[5]

Durometer hardness is related to the elastic modulus of elastomeric materials. Several theoretical efforts have been conducted in the past to establish the relationship between hardness and elastic modulus.[6-7] However, most of these efforts have been based on linear elasticity, even though the indentation in durometer hardness tests involves significant large-scale nonlinear deformation. Gent[6] obtained a simple relation between the elastic modulus and durometer Shore A hardness by approximating the truncated cone indentor geometry as a cylinder and using the classic linear elastic solution for the flat punch contact problem. Briscoe and Sebastian[7] considered the actual shape of the Shore A indentor and linear elasticity theory to obtain a prediction using an iterative solution. The difference between the Gent and the Briscoe and Sebastian results was as large as 15% to 25% for durometer hardness values larger than 50A. In this paper, the ability of durometer Shore hardness tests to provide properties for the stress-strain behavior of elastomers for small to large deformation is assessed. Fully nonlinear finite element analyses are conducted to simulate the durometer hardness tests. The nonlinear stress-strain behavior of the materials is modeled using the Gaussian (neo-Hookean) model and the Arruda-Boyce eight-

* Corresponding author. Ph: 1-617-253-2342; Fax: 1-617-258-8742; email: mcboyce@mit.edu

chain non-Gaussian model. The latter constitutive model captures the limiting extensibility of elastomers (and also of soft tissues[8]) and thus permits evaluation of the relevance of correlating the durometer measurements to limiting aspects of material behavior. Durometer tests for Shore A and Shore D scales are simulated for the Gaussian (neo-Hookean) material. The ability of the model to predict the corresponding Shore D hardness for a given Shore A hardness material acts as a verification. A mapping of Shore A and D values to the elastic modulus predictions is then provided. Comparisons of the new model with prior models are also given. The influence of the limiting extensibility of elastomeric materials on this mapping is assessed.

MODELS

THE MODEL OF DUROMETER HARDNESS TESTS

The durometer hardness test is defined by ASTM D 2240,[1] which covers seven types of durometer: A, B, C, D, DO, O, and OO. Table I shows the comparison of different durometer scales.

TABLE I
COMPARISON OF DIFFERENT SCALES OF DUROMETER TESTS

Type A	10 20 30 40 50 60 70 80 90 100
Type B	10 20 30 40 50 60 70 80 90 100
Type C	10 20 30 40 50 60 70 80 90 100
Type D	10 20 30 40 50 60 70 80 90 100
Type DO	10 20 30 40 50 60 70 80 90 100
Type O	10 20 30 40 50 60 70 80 90 100
Type OO	10 20 30 40 50 60 70 80 90 100

Most commercially available products for durometer tests consist of, according to ASTM D 2240, four components: presser foot, indentor, indentor extension indicating device, and calibrated spring, as shown in Figure 1. The scale reading is proportional to the indentor movement (Figure 2)

$$H = \frac{\Delta L}{0.025mm}, \ \Delta L = L_0 - L \qquad (1)$$

where H is the hardness reading; ΔL is the movement of the indentor.

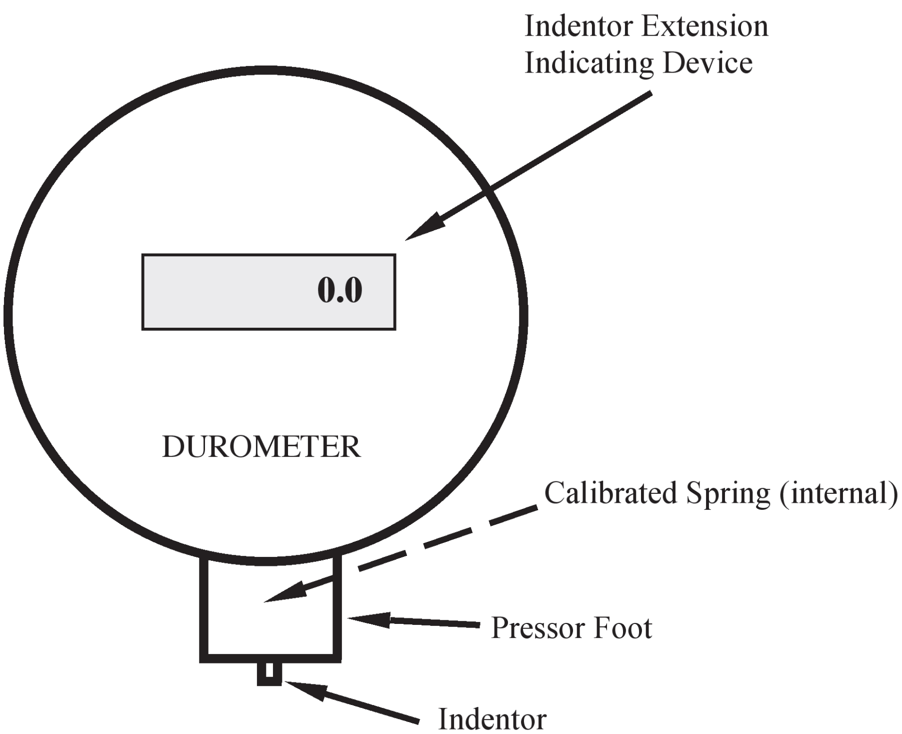

FIG. 1. — A typical durometer.

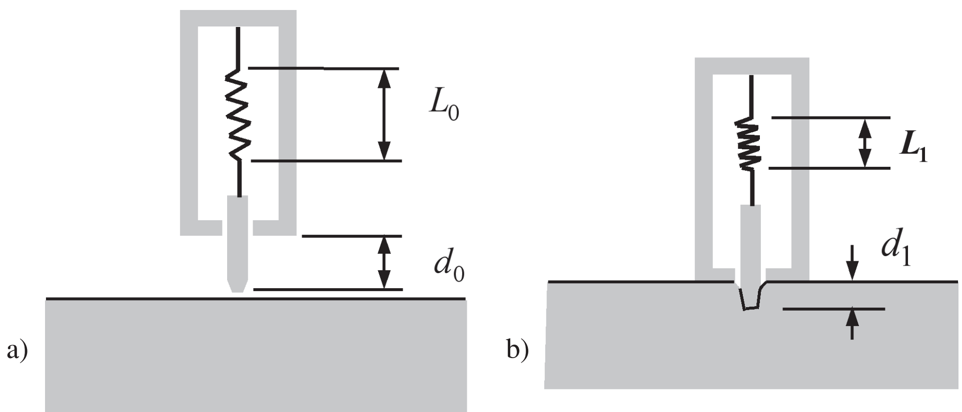

FIG. 2. — Schematics of the working mechanism of durometers.
(a) Before the durometer is pressed down; (b) the durometer is pressed down.

A durometer essentially measures the reaction force on the indentor through the calibrated spring when it is pressed into the material. The relation between the force measured and the movement of the indentor is

$$F = 0.55 + 3\Delta L \tag{2a}$$

for type A, B and O durometers; and

$$F = 17.78\Delta L \tag{2b}$$

for type C, D and DO durometers.

In durometer tests, as the durometer is pressed onto the specimen surface, the indentor penetrates into the specimen, and is simultaneously pressed up into the device as well. This process is depicted in Figure 2, where L_0 is the free length of the calibrated spring; d_0 is the distance between the indentor tip and the presser foot lower surface and according to ASTM D 2240, $d_0 = 2.5$ mm; d_1 is the corresponding distance in the fully loaded condition. Since the lower surface of the presser foot is always in contact with the specimen surface when the reading is taken, it is straightforward to obtain (Figure 2)

$$\Delta L + (d_1 - 0) = 2.5 \tag{3}$$

The indentor is in equilibrium, therefore

$$F_r(h)\Big|_{h=d_1} = F \tag{4}$$

where F_r is the reacting force of the elastomeric specimen due to the indentor penetration denoted by h. Therefore, the objective equations relating the hardness measurement to the stress-strain behavior of the elastomers consist of Equation (3) and Equation (4). The exact form of $F_r(h)$ however is unknown. Gent[6] used the linear elastic Hertz contact solution for the case of a simplified indentor shape. Briscoe and Sebastian[7] considered the actual geometry of the indentor. This method however requires computationally cumbersome numerical methods for the solution. In this paper, we take advantage of developments in nonlinear finite element method (FEM) and numerically simulate the hardness tests to obtain $F_r(h)$ in the form of a force vs indentation, F vs h, curve. The hardness scale reading is then obtained by finding the intercept point as shown in Figure 3.

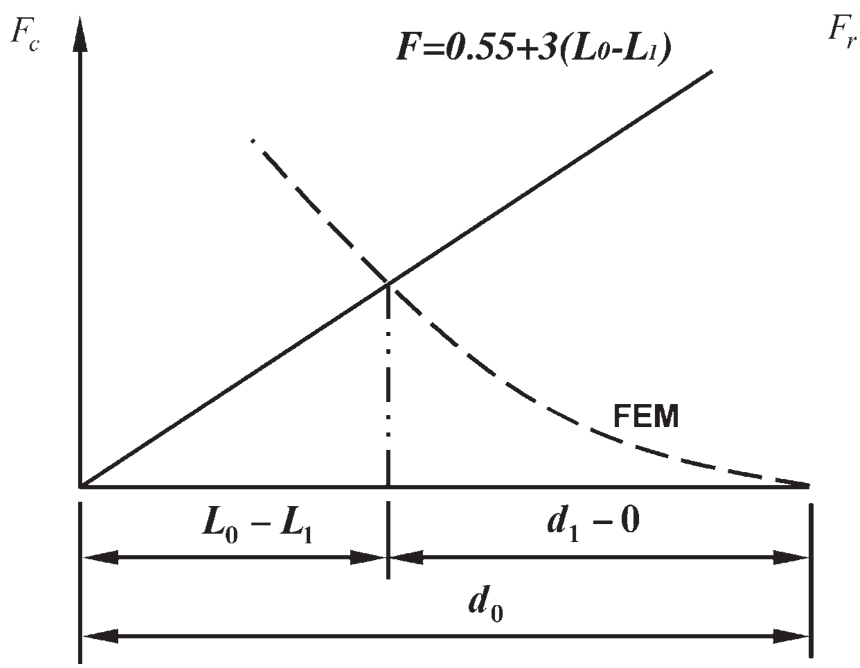

FIG. 3. — Schematic of the method to obtain durometer readings.

FEM MODELS FOR INDENTATION SIMULATIONS

Geometry. — The force vs indentation curve is obtained using a fully nonlinear finite element simulation of the indentation test. Since the indentors have axially symmetric cross sections, it is effective to model the problem as an axisymmetric one. As shown in Figure 4, the vertical boundary AD is subjected to the axisymmetric boundary condition, $u_r|_{AD} = 0$. In order to reduce the influence from the specimen boundary, ASTM D 2240 requires that the test specimen should be at least 6 mm in thickness and the locus of indentation should be at least 12 mm away from any edges. Therefore, in Figure 4, $AB = 15mm$, $BC = 8\ mm$. Due to the existence of friction, the lower surface AB of the specimen cannot move freely along the horizontal direction, $u_r|_{AB} = u_z|_{AB} = 0$.

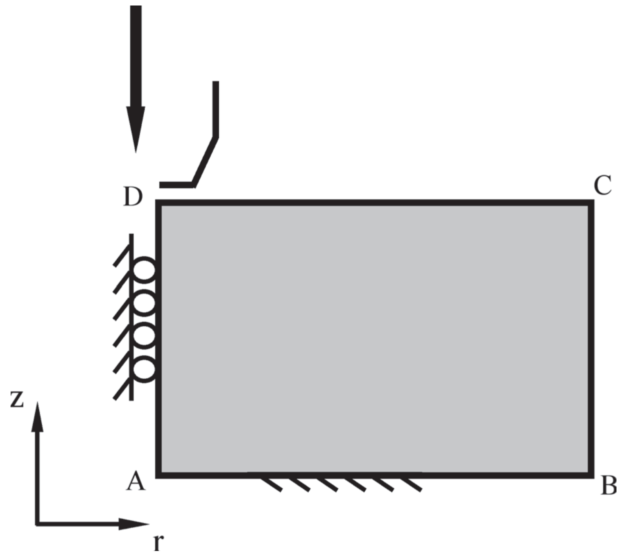

FIG. 4. — The finite element method model for simulations of indentation.

The boundary value problem is solved using the finite element code ABAQUS. Axisymmetric 8-node, hybrid continuum elements with biquadratic interpolation of the displacement field and linear interpolation of pressure are used to model the elastomer. Figure 5 shows the mesh used for the durometer A analyses. The indentor is modeled as a rigid surface since it is much stiffer than the elastomers being tested. The mesh is refined in the vicinity of the contact region where large gradients in stress and strain prevail. Several mesh densities were analyzed and an optimal mesh was finally chosen for use in all simulations. For durometer D analyses, a similar mesh has been used with the exception of the shape of the indentor.

DOCKET ALARM

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

WHAT WILL YOU BUILD? | **sales@docketalarm.com** | **1-866-77-FASTCASE**

fastcase® Smarter legal research.