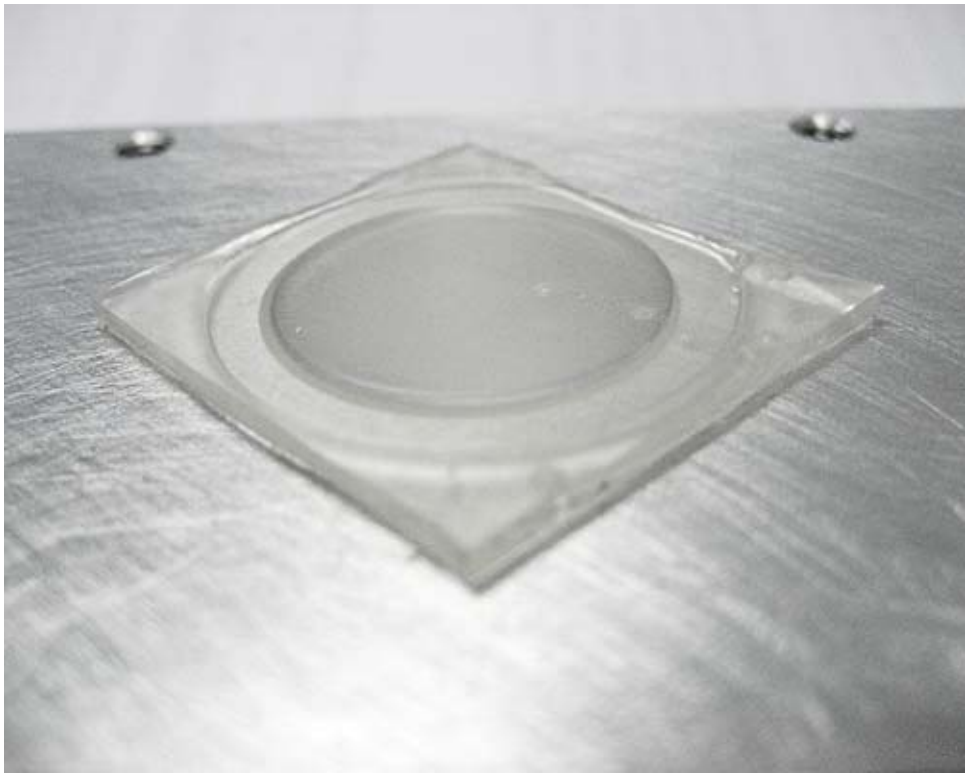
NANOVEA®
A Better Measure.

ELASTIC-PLASTIC RESPONSE OF POLYMER COATING UNDER REPETITIVE IMPACT



Prepared by
Duanjie Li, PhD & Braden Altstatt

6 Morgan, Ste156, Irvine CA 92618 · P: 949.461.9292 · F: 949.461.9232 · nanovea.com

INTRODUCTION

Polymer changes its shape when subjected to a sufficient load. Such a change in shape is called deformation. Elastic deformation takes place when the material returns to its original shape upon removal of the external force. However, when the applied load surpasses the elastic/plastic threshold, the material starts to deform plastically and will not fully recover its original shape. As a result, such plastic deformation is irreversible.

IMPORTANCE OF ELASTIC/PLASTIC PROPERTIES OF POLYMER COATING

The combination of versatile characteristics, cost-effectiveness, and highly tailored production make polymers an excellent candidate to be extensively applied in a variety of industries, as the structural material[i], such as bus windows and eyeglasses, and as protective coatings, such as automotive/floor paints and leather coatings. In this study, protective polymer coatings are applied on the automotive leathers to shield the leather surface from the harmful direct sunlight and make them easy to clean and maintain. Such coatings are subjected to repeated high deformations during daily usage by the passengers or vehicles vibration due to harsh road conditions. Moreover, objects with sharp edges such as keys in the pockets can also potentially damage the surface. Consequently, the resistance to long-term repetitive impact becomes critical to the service lifetime of the coating and leather underneath. As a result, a monitored, controlled and repeatable technique for evaluating the elastic/plastic response of the polymer coatings under a long-term repetitive punch impact is in need.

MEASUREMENT OBJECTIVE

In this application, we designed a new testing setup to simulate the repetitive impact on the protective polymer coating and investigated its elastic/plastic response as a function of time using the Nanovea Mechanical Tester in Microindentation mode.

Fig. 1: The setup of the elastic/plastic property measurement on the polymer coating.

MEASUREMENT PRINCIPLE

Nanoindentation is based on the standards for instrumented indentation, ASTM E2546 and ISO 14577. It uses an established method where an indenter tip with a known geometry is driven into a specific site of the material to be tested, by applying an increasing normal load. When reaching a pre-set maximum value, the normal load is reduced until complete relaxation occurs. The load is applied by a piezo actuator and the load is measured in a controlled loop with a high sensitivity load cell. During the experiment the position of the indenter relative to the sample surface is precisely monitored with high precision capacitive sensor.

The resulting load/displacement curves provide data specific to the mechanical nature of the material under examination. Established models are used to calculate quantitative hardness and modulus values for such data. Nanoindentation is especially suited to load and penetration depth measurements at nanometer scales and has the following specifications:

Maximum displacement (Dual Range)	: 50 μm or 250 μm
Depth Resolution (Theoretical)	: 0.003 nm
Depth Resolution (Noise Level)	: 0.15 nm
Maximum force	: 400 mN
Load Resolution (Theoretical)	: 0.03 μN
Load Resolution (Noise Floor)	: 0.3 μN

Analysis of Indentation Curve

Following the ASTM E2546 (ISO 14577), hardness and elastic modulus are determined through load/displacement curve as for the example below.

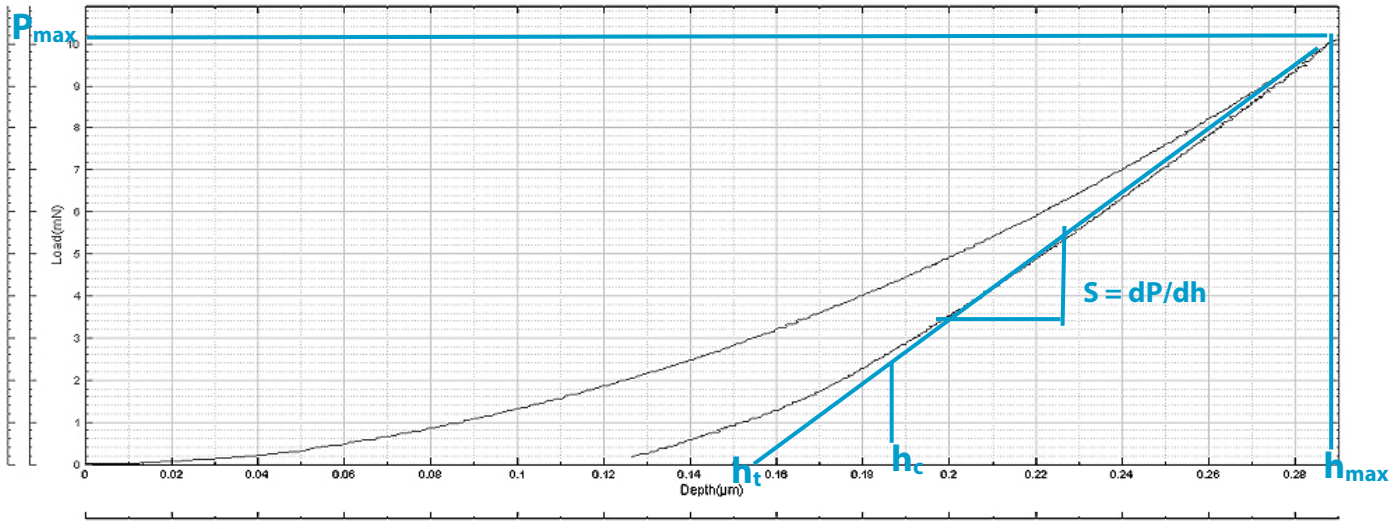


Fig. 2: Load-displacement curve of nanoindentation.

Hardness

The hardness is determined from the maximum load, P_{max}, divided by the projected contact area, A_c:

$$H = \frac{P_{\max}}{A_c}$$

Young's Modulus

The reduced modulus, E_r, is given by:

$$E_r = \frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A_c}}$$

Which can be calculated having derived S and A_C from the indentation curve using the area function, A_C being the projected contact area. The Young's modulus, E, can then be obtained from:

$$\frac{1}{E_r} = \frac{1-\nu^2}{E} + \frac{1-\nu_i^2}{E_i}$$

Where E_i and ν_i are the Young's modulus and Poisson's ratio of the indenter and ν the Poisson's ratio of the tested sample.

How are these calculated?

A power-law fit through the upper 1/3 to1/2 of the unloading data intersects the depth axis at h_t. The stiffness, S, is given by the slope of this line. The contact depth, h_c, is then calculated as:

$$h_c = h_{\max} - {}^{3P_{\max}}\!/_{4S}$$

The contact Area A_c is calculated by evaluating the indenter area function. This function will depend on the diamond geometry and at low loads by an area correction.

For a perfect Berkovich and Vickers indenters, the area function is $A_c=24.5h_c^2$. For Cube Corner indenter, the area function is $A_c=2.60h_c^2$. For Spherical indenter, the area function is $A_c=2\pi Rh_c$, where R is the radius of the indenter. The elastic components, as previously mentioned, can be modeled as springs of elastic constant E, given the formula: $\sigma = E\varepsilon$ where σ is the stress, E is the elastic modulus of the material, and ε is the strain that occurs under the given stress, similar to Hooke's Law. The viscous components can be modeled as dashpots such that the stress-strain rate relationship can be given as $\sigma = \eta\frac{d\varepsilon}{dt}$, where σ is the stress, η is the viscosity of the material, and $d\varepsilon/dt$ is the time derivative of strain.

Since the analysis is very dependent on the model that is chosen, Nanovea provides the tool to gather the data of displacement versus depth during the creep time. The maximum creep displacement versus the maximum depth of indent and the average speed of creep in nm/s is given by the software. Creep may be best studied when loading is quicker. Spherical tip is a better choice.

Other possible measurements by Nanovea Mechanical Tester:

Stress-Strain & Yield Stress, Fracture Toughness, Compression strength, Fatigue testing and many others.

TEST CONDITIONS

The evolution of elastic/plastic response of the polymer coatings was studied under a long-term repetitive punch impact. The polymer film (~1.6 mm thickness) was mounted in a custom sample holder as shown in Fig. 1. The edge of the film was fixed and the center hole has a diameter of 20 mm. As illustrated in Fig. 3, linear load/unload cycles were applied to the polymer film by a stainless steel ball of 10 mm diameter. The test conditions are summarized in Table 1.

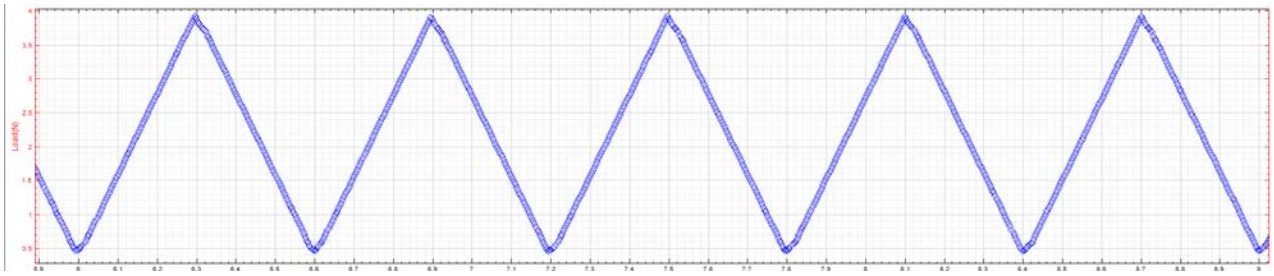


Fig. 3: The loading cycle vs. Time during the test.

Maximum Load	4N
Cycles	150
Loading Rate	12
Unloading Rate	12

Table 1: Summary of test conditions.

RESULTS AND DISCUSSION

The Deformation displacement vs. Time and Load-displacement curves are displayed in Fig. 4 and Fig. 5, respectively, and the corresponding results are summarized in Table 2. As the 4 N loading-unloading cycles were applied, the maximum deformation displacement of the tested membrane progressively increased from 1468 to 2825 μm, and the sample did not return to its original shape. This indicates that the permanent (plastic) deformation was created by the repeated punching motion of the steel ball. The deformation at the maximum load of 4 N during each cycle increased at a high rate in the first few cycles and then progressively slowed down and reached a relatively constant value. This can be related to the creeping behavior of the tested polymer membrane.

It is also observed that the oscillation amplitude of the deformation displacement decreased from 836 to 404 μm, indicating that the polymer membrane exhibits increased stiffness and a loss of flexibility after the load cycles. The flexibility of the protective coating for the leather seats is an important characteristic, the deterioration of which may result in reduction in comfort for the passengers and possible delamination from the leather surface.

In summary, the repetitive punch impact test in this study allows us to simulate the usage of the materials under such work conditions and evaluate the evolution of their elastic/plastic behaviors in a monitored and controlled manner. Such an experimental setup can also be possibly used to investigate the fatigue behavior of thin films or membranes.

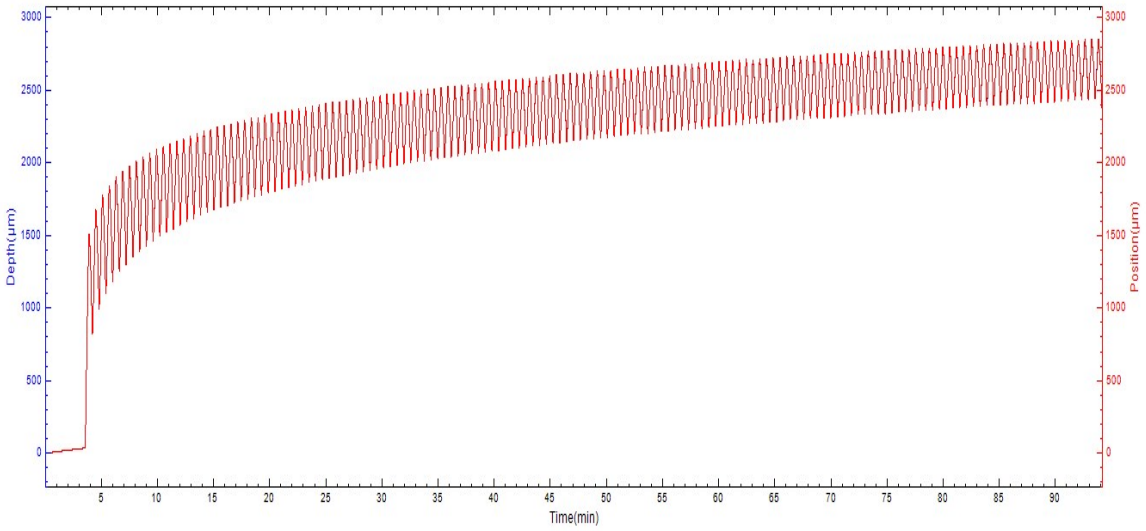


Fig. 4: Deformation displacement vs. Time.

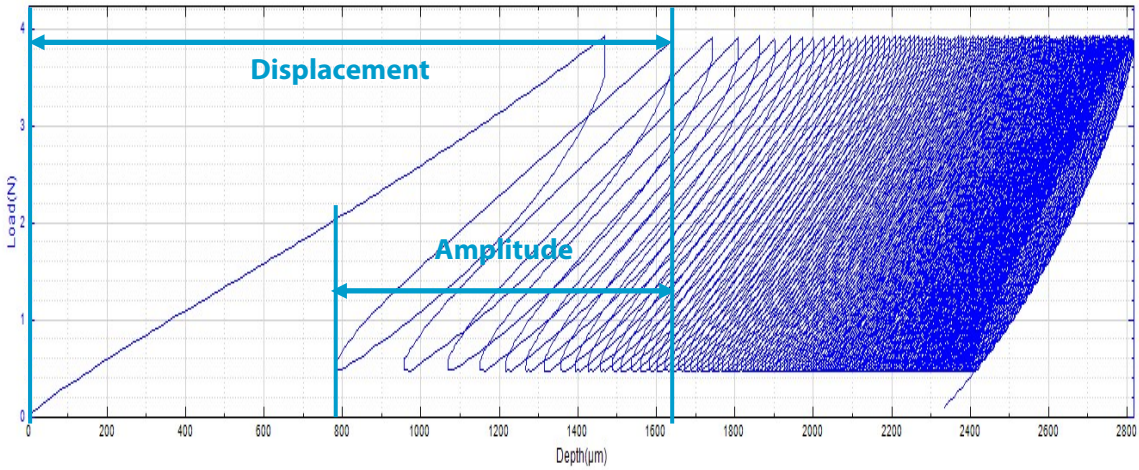


Fig. 5: Load-displacement curve.

Maximum Load (N)	4
Initial Displacement (μm)	1468
Final Displacement (μm)	2825
Increase of Deformation Displacement (μm)	1357
Amplitude Initial (μm)	836
Amplitude Final (μm)	404

Table 2: Summary of change of displacement and amplitude.

CONCLUSION

In this study, we developed an experimental method to assess the effect of repeated external impacts to the elastic/plastic behaviors of the polymer coatings in a controlled and monitored manner. The tested polymer membrane exhibits increased stiffness and a loss of flexibility after the loading cycles. The deterioration of the flexibility can lead to reduction in comfort for the passengers and possible delamination and fracture of the protective layer on the leather. Such an experimental setup also provides a potential solution of investigating the fatigue behavior of flexible thin films or membranes.

The Nanovea Mechanical Testers provide unmatched multi-function Nano and Micro/Macro modules on a single platform. Both the Nano and Micro/Macro modules include ISO and ASTM compliant scratch tester, hardness tester and wear tester modes, providing the widest and most user friendly range of testing available on a single module.

To learn more about Nanovea Mechanical Tester or Lab Services.

---

[i] **A.D. Mulliken, M.C. Boyce, Corresponding author contact informationMechanics of the rate-dependent elastic–plastic deformation of glassy polymers from low to high strain rates, International Journal of Solids and Structures, Volume 43, Issue 5, March 2006, Pages 1331–1356**