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Finite-element analysis of the deformation of thin Mylar films due to measurement forces

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Abstract

Significant deformation of thin films occurs when measuring thickness by mechanical means. This source of measurement error can lead to underestimating film thickness if proper corrections are not made. Analytical solutions exist for Hertzian contact deformation, but these solutions assume relatively large geometries. If the film being measured is thin, the analytical Hertzian assumptions are not appropriate. ANSYS is used to model the contact deformation of a 48 gauge Mylar film under bearing load, supported by a stiffer material. Simulation results are presented and compared to other correction estimates. Ideal, semi-infinite, and constrained properties of the film and the measurement tools are considered.

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1. Introduction

This work is motivated by the need to accurately measure the thickness of a 48 gauge[1] Mylar® polyethylene terephthate film [1] for quality control in production processes and for long-term surveillance. The American Society for Testing and Materials (ASTM) has published standard ASTM E252-06 [2] for measuring thickness of films 0.002" and thinner based on square area and known material density. This method is employed for Mylar procurement. However, in-house processing causes density changes from absorption of organic molecules, including significant amounts of solvent. This can cause polymer swell and changes in crystallinity, both of which impact density. [3] Thickness changes are known to occur due to polymer swell and web shrinkage from steps at elevated temperatures. As entrained solvent and changes to crystallinity can also change film index of refraction, optical methods are difficult to employ with required precision. A mechanical displacement measurement method may be the best option, but inherent errors must be understood, reported, and corrected for.

ASTM has another standard related to measurement of solid electrical insulating materials by mechanical means, referenced as ASTM standard D374-99 (2004) [4]. This method outlines test procedures for the measurement of thin film electrical insulators such as Mylar film down to 0.001" thickness. The typical approach is to use a bench top micrometer, in which the film is placed on a flat steel anvil, and a probe with a spherical tip is pressed onto the top surface of the film with a known or controlled force. The probe is located on an instrumented linear displacement system such that the position of the tip is well known. Hereafter, we use the term ball to describe the spherical tip at the end of the measurement probe. In addition to possible measurement errors in the linear displacement transducer, there is error in the measured free-standing film thickness from the deformation of the film due to elastic compression by the ball. The error associated with elastic compression becomes excessive for films thinner than 0.001".

ASTM D374-99 (2004) presents an analytical expression for calculating the film indentation so that this effect can be corrected in the final measurement; however, the expression is for a perfectly rigid sphere pressing onto a semi-infinite elastic solid. While this may be sufficient for films of moderate thickness (>0.001"), as the film thickness decreases the accuracy of this calculation will also decrease. This fact is recognized in the standard, but it is left to the user to understand and appropriately manage this error. To quote from the standard in section X1.1.5, "In the absence of any better theoretical model, the equations for a … spherical die indenting a semi-infinite solid are presented and adapted to the thickness measurements in the hope that further work is stimulated based on adapting the semi-infinite model to finite size models" [4]. This report documents work done using finite-element analysis to determine the error associated with the semi-infinite elastic solid assumption, and to determine more accurate indentation depths by modeling real deformations of ball, anvil, and thin film for this specific measurement based on documented materials' properties. The method is applied to the specific case of 48 gauge Mylar, nominally 12.2 microns thick.

---

[1] For films, 1 gauge unit is 0.00001", or 0.00048" for 48 gauge film. 1 inch = 25.4 mm exactly.

2. Analytical solution for semi-infinite solid

An analytical expression for the relative deflection of two elastic spheres pushed against each other is derived by Timoshenko and Goodier [5], and is given as:

$$d = \left[\frac{9\pi^2}{16}\frac{P^2(k_1 + k_2)^2(R_1+R_2)}{R_1R_2}\right]^{1/3} \tag{1}$$

where k_1 and k_2 are defined for each of the two spheres as:

$$k_n = \frac{1 - {\nu_n}^2}{\pi E_n} \tag{2}$$

d is the deflection; where P is the applied force, R_n is the radius, ν_n is Poisson's ratio, and E_n is Young's Modulus for each of the two spheres. To solve for the indentation of a perfectly rigid sphere pressing on a semi-infinite elastic solid, this equation can be re-written with $1/R_1$ and $1/E_2$ set equal to zero. The resulting expression is:

$$d = \left[\frac{9P^2(1 - \nu^2)^2}{16E^2R}\right]^{1/3} \tag{3}$$

where P is the applied force, R is the radius of the rigid contacting sphere, ν is Poisson's ratio and E is Young's Modulus of the semi-infinite solid. This is the same equation presented in ASTM D374-99 (2004). Solutions for the elastic compression of various geometries in Hertzian contact have also been published, for example, by Puttock and Thwaite [6].

To determine the significance of calculated indentation of 48 gauge (12.2 micron thick) Mylar we consider the example where a measurement tool applies a load force of 1 N, using a contacting steel sphere with a 5 mm radius. Using the Mylar manufacturer's specifications [1] for Young's Modulus of 5 GPa, and Poisson's ratio of 0.38, Eq. 3 predicts an indentation into the Mylar film of 1.49 microns, or a deformation of 12.2% of the total thickness for measurement of a 12.2 micron thick Mylar sheet. Given this large deformation as a percentage of the total thickness it is necessary to consider whether or not the approximation of a semi-infinite solid is appropriate. As the thickness of the Mylar decreases, the supporting substrate becomes a larger factor and the elastic properties of the support need to be considered in order to better approximate the compression of the elastic Mylar. ANSYS version 13.0, a commercial finite-element analysis software package, is used to simulate these conditions.

2.1. ANSYS validation results

For validation of the ANSYS model, a perfectly rigid sphere with radius of 5 mm was pressed into both a steel and a Mylar semi-infinite surface with a force of 10 N. Elasticity of the semi-infinite surface was considered perfectly linear with no plasticity or yield. Section X1.3.2 of [4] provides guidance to avoid inelastic deformation based on yield stress of the

dielectric under test. The resulting displacement of the sphere was compared to this closed form solution. Results are shown in Table 2-1

Table 2-1: Model validation comparison for rigid ball pressing on a semi-infinite solid of steel and Mylar.

	Steel	Mylar
Closed-form Solution	0.615 microns	6.91 microns
ANSYS Solution	0.614 microns	6.88 microns
Percent error	-0.3 %	-0.4 %

The ANSYS model was constructed as an axisymmetric analysis about the centerline of the applied load. The semi-infinite solid was modeled as a cylinder with 30 mm thickness and 30 mm radius, with the displacement constrained on the bottom of the cylinder. This size was selected to be large enough to approximate a semi-infinite region, and increasing this size in the simulation did not result in a significant change to the solution. Accuracy of the solution is very dependent on the element refinement at the point of contact between the ball and the surface, and on the contact stiffness. The contact stiffness was set to a value of 100 (compared to the default of 1), to ensure that contact penetration was better than a factor of 100 less that the total displacement. The contact between the ball and the surface was assumed to be frictionless, as is also the case for the Timoshenko and Goodier derivation.

2.2. Steel Ball into Steel Semi-Infinite Solid

In the process of measuring film thickness using a bench-top micrometer, a zeroing step is performed where the steel ball is pressed directly onto the steel anvil. To account for the compliance in both the ball and the anvil, Eq. 1 can be re-written assuming that E_1 and E_2 are equal, ν_1 and ν_2 are equal, and with $1/R_1$ equal to zero. The indentation of a compliant ball into a semi-infinite elastic solid of the same material is given by the following equation:

$$d = \left[\frac{9P^2(1-\nu^2)^2}{4E^2R}\right]^{1/3} \tag{4}$$

When the ball is the same elastic material as the anvil then the indentation is increased by $\sqrt[3]{4}$, or by a factor of 1.59, compared to the solution in Eq. 3 where the ball is assumed to be perfectly rigid.

3. Mylar Sheet on a Rigid Anvil

To evaluate the validity of Eq. 3 when used with a 12.2 micron thick sheet of Mylar, an ANSYS model was created that assumes a perfectly rigid sphere indenting on a thin Mylar sheet resting on a perfectly rigid and flat anvil. This is the simplest model to create in ANSYS, as the sphere and anvil do not need to be meshed. By adjusting the boundary conditions applied to the bottom of the Mylar sheet, the interface between the Mylar and the anvil can be modeled as frictionless or as “sticky,” where no slip is allowed. The reality of this load case is somewhere in between these two extremes based on the coefficient of friction between the Mylar and the anvil material. The zero-friction case is expected to most

closely approximate the true solution, but both results have been modeled in order to capture the maximum possible error in this assumption. A schematic showing this model geometry is shown in Figure 3-1. The ANSYS APDL input script for the model is included in Appendix A.

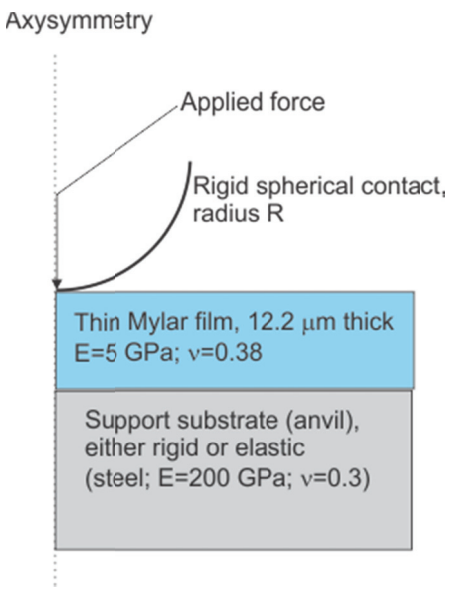


Figure 3-1: Schematic showing geometry of ANSYS model.

In practice different sized spheres are typically available for use in bench top micrometers used to make thickness measurements, so a simulation was run using radii of 1.6 mm, 2.5 mm, 5.0 mm, and 11.0 mm. The results of indentation vs. applied force are shown in Figure 3-2 for the zero-friction boundary conditions between the Mylar and the anvil. For comparison purposes, this figure also shows the indentation predicted by Eq. 3 for each ball radius into a semi-infinite elastic solid of Mylar.

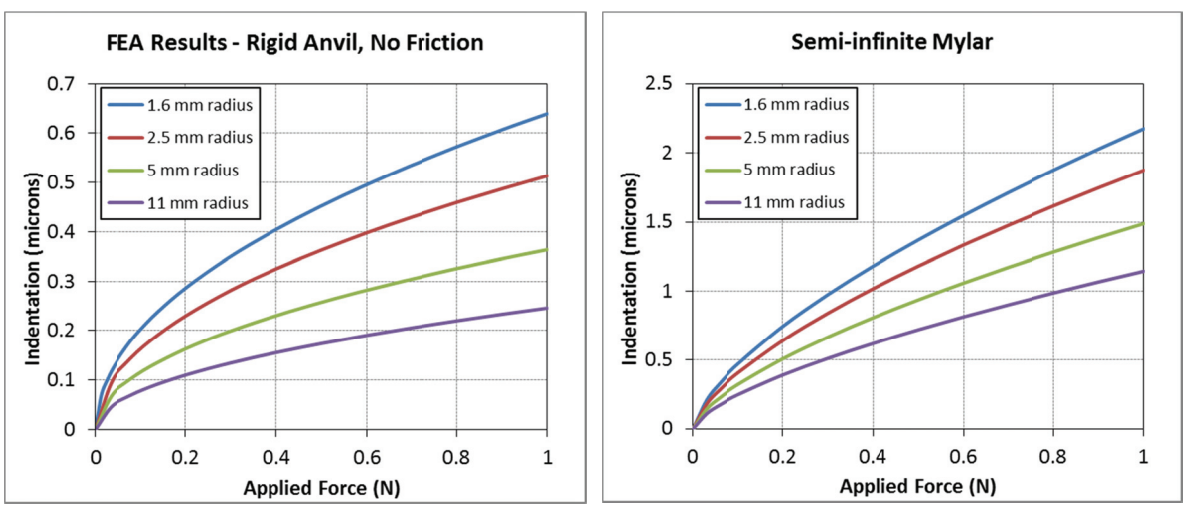


Figure 3-2: Indentation vs. applied force for both the FEA solution and the closed-form semi-infinite solution.

While the general appearance of these plots is very similar, there is a significant difference in scale for the Y-axes, with the finite-element predicted indentation into a 12.2 micron thick layer of material being substantially less than the closed-form equation would indicate for the case of a semi-infinite solid. It is logical that the thin compliant Mylar backed by the rigid anvil is modeled to deflect less than a much thicker semi-infinite piece of compliant Mylar.

For this range of applied force and radius, the maximum difference between the zero-friction and no-slip boundary conditions can be as large as 0.12 microns for the smallest sphere and highest force considered. The no-slip condition showed less indentation than the no-friction case by 15% to 19% of the no-friction solution. This would be expected, as the no-slip condition is more constrained. This difference captures the maximum error in the FEA solution due to friction between the Mylar and the anvil. Puttock and Thwaite [6] have reported good agreement between experimental results and the Hertzian model with no friction for the type of surface finish used in national metrological institutes (NMI's).

The reduced indentation of the thin Mylar sample compared to the semi-infinite solution will result in improved accuracy of the thickness measurement *if* no correction is applied to account for this indentation. However, if the semi-infinite correction is applied as indicated in ASTM D374-99 (2004) then the calculated free-standing film thickness will have a significant positive error (over-estimation of the thickness) due to the inaccuracy of Eq. 3 in predicting the true indentation into a thin sample. Depending on the force applied by the measurement tool, the error introduced by this correction can easily exceed the error that would be present without any correction.

To further illustrate the difference between the closed-form solution and the finite-element solution, the percent error of the semi-infinite solution relative to the FEA prediction is listed in Table 3-1 for multiple applied loads and radii.

Table 3-1: Percent error of semi-infinite closed form solution relative to FEA prediction for sphere indention into 12.2 micron thick Mylar sheet.

	Applied Force		
Ball Radius	**0.1 N**	**0.5 N**	**1.0 N**
1.6 mm	132%	202%	240%
2.5 mm	149%	225%	265%
5.0 mm	179%	264%	309%
11.0 mm	217%	315%	365%

4. Mylar Sheet on Elastic Steel Anvil

To further improve the accuracy of the finite-element solution, a model was created where the assumption of a perfectly rigid anvil was removed. In this model the anvil is modeled as a steel plate, with a Young's modulus of 200 GPa, and a Poisson's ratio of 0.3. This is in comparison to the previous section where the anvil was assumed to be perfectly rigid. The plate thickness and size in the model was very large such that it could be considered semi-infinite. The boundary between the Mylar and the steel anvil was again modeled for both the zero-friction and the no-slip conditions. The ANSYS APDL input script for the model is

included in Appendix A. The resulting indentation vs. applied force and radius is shown in Figure 4-1. Because some compliance exists in the steel anvil, the indentation of the sphere is slightly larger than the previous case with a perfectly rigid anvil. The difference between indentations for the rigid anvil and steel anvil can be as high as 15% of the steel anvil solution across the range shown in the plot.

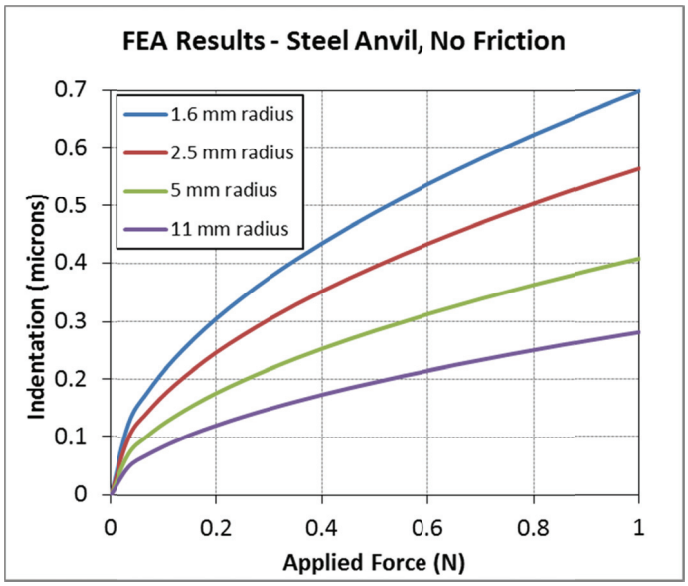


Figure 4-1: Indentation vs. force and radius for a 12.2 micron thick Mylar sheet assuming no friction and including compliance of the steel anvil.

The steel-anvil condition was also modeled with a no-slip boundary condition between the steel and the Mylar. Again, this would represent a worst-case friction condition and captures the maximum error that could be introduced due to friction at this interface. For the case where the anvil was modeled as steel, the no-slip condition showed less indentation than the no-friction case by 16% to 17% of the no-friction solution.

As this model is considered the most accurate of the three approaches considered in this report (semi-infinite, rigid anvil, and elastic anvil), a curve-fit has been developed across all the finite-element results shown in Figure 4-1. This will allow the indentation to be calculated for any force up to 1 N, and any ball radius up to 11 mm, for the case of a 12.2 micron thick Mylar sheet on a steel anvil. It is important to recognize the limitations of this curve fit; it applies *only* within these limited boundaries. It is expected that the fit coefficients would change for thicknesses significantly different from 12.2 microns, for different film or anvil materials, and for loads or radii outside of the fit boundaries. Within these constraints, the fit for indentation is given as:

$$d = \frac{0.033P^{0.517}}{R^{0.474}} \tag{5}$$

where d is the indentation in microns, P is the applied load in Newtons, and R is the ball radius in meters. Confidence bounds for d in Eq. 5 are (+0%, -17%) based on no friction at the interfaces to no-slip at the interfaces.

The stiffness of the spherical contact (in mechanical comparators, this is typically steel, tungsten carbide, or ruby) is significantly greater than the Mylar. Calculations using a semi-infinite thickness of Mylar show that the effect of using a rigid sphere versus a steel sphere are less than 2%, as shown in Table 4-1. Therefore, we use a rigid sphere contact for the simulations.

Table 4-1: Analytical total displacement for an elastic sphere of increasing stiffness into a semi-infinite Mylar body.

Mylar: E=5 GPa; ν=0.38	Sphere: Steel Force: 1 N E=200 GPa; ν=0.3	Sphere: Tungsten Carbide Force: 1N E=724 GPa; ν=0.3	Sphere: Perfectly rigid Force: 1N
Sphere Radius	**Total displacement**	**Total displacement**	**Total displacement**
1.6 mm	2.21 μm	2.19 μm	2.18 μm
2.5 mm	1.91 μm	1.88 μm	1.87 μm
5 mm	1.51 μm	1.50 μm	1.49 μm
11 mm	1.16 μm	1.15 μm	1.14 μm

4.1. Multiple Stacked Mylar Layers

To decrease the thickness uncertainty per layer due to measurement indentation, multiple layers can be stacked on top of one another and measured together. The total indentation will be larger, but the average indentation per layer will be reduced. This can also be an effective approach for reducing other measurement uncertainties in the system. A plot of the total indentation into five stacked layers of Mylar is shown in Figure 4-2.

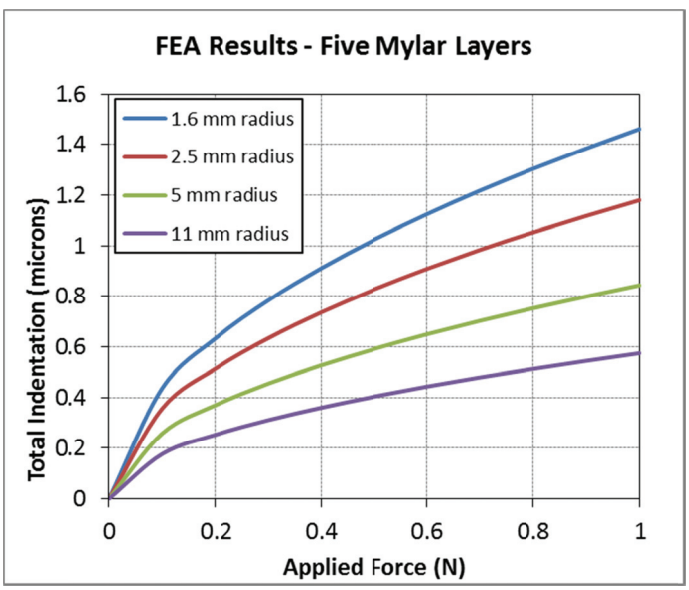


Figure 4-2: Total indentation of five stacked Mylar layers, assuming zero friction at each interface and with a compliant steel anvil.

When the model was executed assuming no slip at each of the Mylar surfaces the indentation was less than the zero-friction case by 16% of the zero-friction solution, representing the

maximum error due to friction at this interface. A curve fit of the 5-layer stacked result is given in Eq. 6 for the total indentation of the Mylar stack.

$$d = \frac{0.065P^{0.516}}{R^{0.483}} \tag{6}$$

When compared to the single-layer model as shown in Figure 4-1, the five layer stack total indentation is approximately a factor of 2.1 greater but this increased indentation is spread out over five layers instead of just one. The resulting per-layer indentation is between 41% and 42% of the single-layer solution. The ANSYS input macro for this analysis is included in Appendix A. Confidence bounds for *d* in Eq. 6 are (+0%, -16%) based on no friction at the interfaces to no-slip at the interfaces.

5. Mylar Yield Stress

We do not simulate or provide new information on determining yield stress of Mylar during measurement. For completeness we include calculations to ensure that the measurement conditions modeled here will not cause inelastic deformation of the Mylar. ASTM D374-99 (2004) [4] section X1.3.2 provides an equation for stress on a film during measurement.

$$Stress = 0.5784\left(\frac{E}{1-v^2}\right)^{2/3}\left(\frac{P}{R^2}\right)^{1/3} \tag{7}$$

Stress should be < 30% of yield stress to be certain that no inelastic deformation occurs. An expected yield stress of 28 kpsi (190 MPa) for 48 gauge Mylar can be found in the DuPont Product Description for Mylar C [7]. Values in the table exceeding 57 MPa are shaded yellow and should be avoided if possible.

Table 5-1: Stress in MPa for conditions in Table 3-1

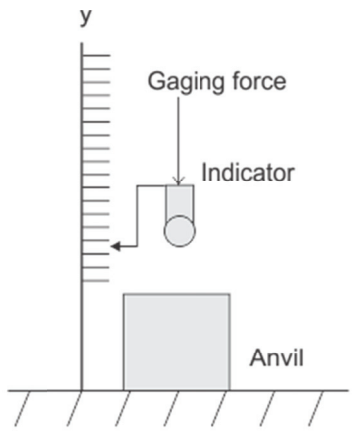
	Applied Force		
Ball Radius	**0.1 N**	**0.5 N**	**1.0 N**
1.6 mm	64	109	137
2.5 mm	47	81	102
5.0 mm	30	51	64
11.0 mm	18	30	38

6. Measurement Guidelines and Examples

Measurement of the thickness of a flat object can typically be performed on a mechanical comparator. Figure 6-1 shows a schematic sketch of a mechanical comparator. The measurement procedure, using a mechanical comparator, is typically:

1. Set up the equipment
2. Use a known standard (such as a gage block)
3. Verify the comparator reading using the known standard, or calibrate the comparator at time of use using a minimum of 2 gage blocks of appropriate size difference.
4. Measure the unknown

If the comparator, the standard, and the unknown are all the same materials then no correction for Hertzian contact need be made because the contact deformations will be the same for the standard and for the unknown.



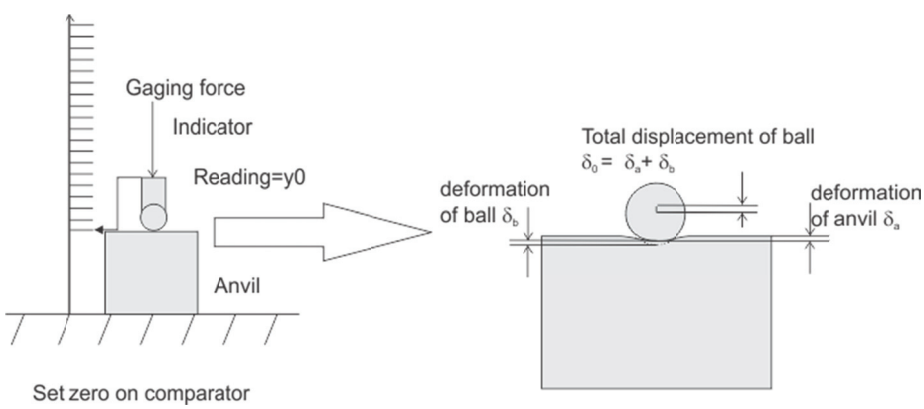
Generic mechanical comparator
(indicator is any readout, including LVDT)

Figure 6-1: Schematic sketch of a mechanical comparator or benchtop micrometer

When taking the zero measurement (comparator stylus tip against the anvil), the gaging force induces elastic compression in both the spherical tip and the anvil. This is illustrated in Figure 6-2. At the zero setting, the comparator reading will be:

$$y_0 = y_r - \delta_0 \tag{8}$$

where y_0 is the reading, y_r is some reference value, and δ_0 is the displacement due to elastic compression.



Set zero on comparator

Figure 6-2: Setting at zero for the comparator.

When measuring an unknown of thickness t with the same material properties as the spherical tip and anvil, the comparator would be as shown in Figure 6-3.

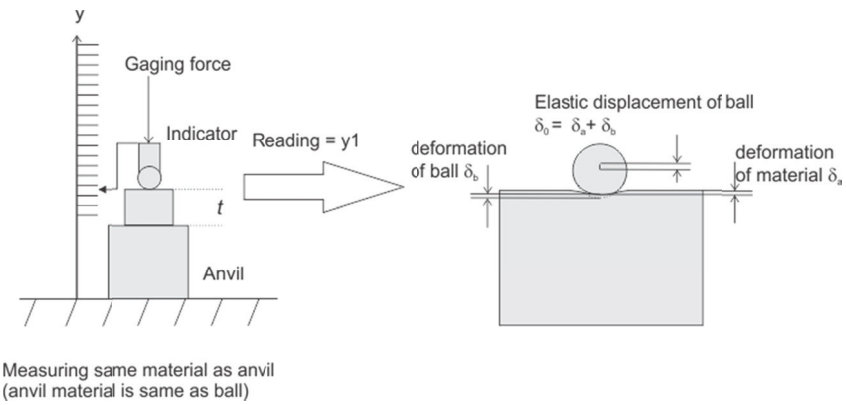


Figure 6-3: Measuring an object of the same material as ball and anvil.

The reading when measuring an object of nominal thickness t is:

$$y_1 = y_r + t - \delta_0 \tag{9}$$

Calculating the measured thickness t_m as the difference between the measurement reading and the zero reading,

$$t_m = y_1 - y_0 = (y_r + t - \delta_0) - (y_r - \delta_0) = t \tag{10}$$

For similar materials, the elastic compressions are the same and cancel out; therefore, the measured value is the thickness of the material. When measuring a material with different elastic properties as shown in Figure 6-4, the elastic compression is different between the zero reading and the unknown measurement. The sample measurement is:

$$y_2 = y_r + t - \delta_2 \tag{11}$$

where δ_2 is the total elastic deformation of the anvil, ball, and sample when the sample is a different material from the comparator. In order to obtain the actual thickness t, one needs to account for the different elastic deformations, using the following measurement equation:

$$t = y_2 - y_0 + (\delta_2 - \delta_0) \tag{12}$$

where the value for δ_0 is found using equation 4 and δ_2 is determined using equation 5.

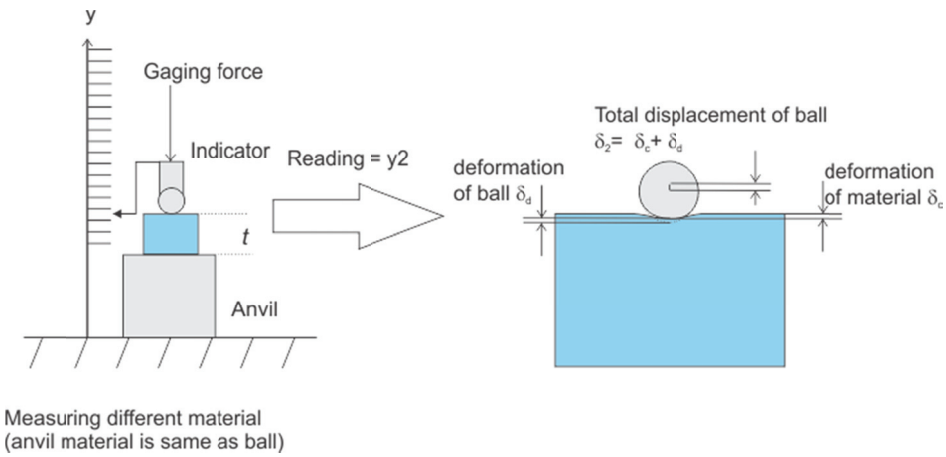


Figure 6-4. Measuring a material of nominal thickness *t* with different elastic properties.

When making measurements for product acceptance, the general requirements 9900000 [8] state that "… the collective uncertainty of the measuring equipment shall not exceed 25% of the acceptable tolerance (minimum 4:1 test accuracy ratio) for each characteristic being inspected." If the Test Accuracy Ratio (TAR) is less than 4, the acceptance limits must be guard-banded. TAR equals the required tolerance divided by the equipment accuracy. See ASME standard B89.7.3.1 [9] for details on the use of TAR and guard-banding using stringent acceptance rules. A thorough analysis of measurement uncertainty, following guidance from ISO [10] or NIST [11] is outside the scope of this report.

6.1. Simulated Measurement Example

We present an example of the use of deformation correction and application of general requirements 9900000. Consider 48 gauge Mylar with a nominal 12.2 micron thickness, and an acceptable tolerance of ± 0.5 micron. We can choose between two Linear Variable Differential Transformers (LVDT) with characteristics found in Table 6-1. In these examples, the measurements have been made according to equation 12 using equation 5 to calculate deformation corrections.

Table 6-1: Example of LVDT characteristics.

	LVDT #1	LVDT #2
Resolution	0.01 microns	0.001 microns
Calibrated Accuracy	±0.2 microns	±0.020 microns
Probe Radius	11 mm	11 mm
Probe Force	0.12 Newtons	0.12 Newtons

Using the equipment in Table 6-1, and assuming a steel stylus, steel anvil, and steel gage blocks, we calculate the deformation per equation 4:

$$\delta_0 = 39 \text{ nm} \tag{13}$$

When measuring against a mylar film of nominal 12.2 micrometer thickness, the deformation per equation 5 is:

$$\delta_2 = 94 \text{ nm} \tag{14}$$

The correction for deformation is[2]:

$$\left(\delta_2 - \delta_0\right) = 54 \text{ nm} \tag{15}$$

Therefore, measurements of mylar film must have a 54 nm correction added to the measured value to obtain the undeformed film thickness.[3] This correction is applicable to both LVDTs, as the instruments apply the same probing force, and use the same probe radius.

From the specifications, the width of the acceptable tolerance zone is 1.0 micron (±0.5 micron). Using LVDT #1, the equipment accuracy width is 0.4 micron, and the TAR using LVDT #1 is 1.0/0.4, or 2.5:1. Because the TAR is less than 4:1, guard-banding must be used. The stringent guard-banding rule given in 9900000 is to reduce the acceptance zone by the equipment accuracy. The acceptance zone is ±0.5; the equipment accuracy is ±0.2. The guard-banded acceptance zone is ±0.3. Therefore, only product with measurements between 11.9 micron and 12.5 micron (12.2±0.3) is accepted. This ensures that false acceptance of product due to instrument accuracy and measurement uncertainty is minimized. Table 6-2 shows a measurement worksheet using artificial data using LVDT #1:

---

[2] The calculations are shown here to two significant figures, but are carried in full precision in the calculator memory.

[3] If we had assumed semi-infinite thickness for the mylar, the deformation correction would have been (283 nm – 39 nm)=244 nm for this particular probe geometry and probing force.

Table 6-2: Measurement worksheet using artificial data with LVDT #1, 11 mm contact radius, 0.12 N force.

Operator:		*I.M. Technologist*								
Date/time:		*mm/dd/yyyy 10:15am*								
Environment meets specs?			*Yes*							
Sample #	Set 0?	1.000 mm block	1.010 mm block	OK to continue? (read ±0.0002 mm)	Film on top of 1.000 mm	Deformation corr (mm)	Film thickness (mm)	Upper limit (mm)	Lower limit (mm)	Pass/Fail?
1	Y	1.00001	1.01000	Y	1.01220	0.00005	0.01224	0.01250	0.01190	P
2	Y	1.00002	1.01002	Y	1.01194	0.00005	0.01197	0.01250	0.01190	P
3	Y	1.00000	1.01000	Y	1.01235	0.00005	0.01240	0.01250	0.01190	P
4	Y	0.99999	1.01001	Y	1.01245	0.00005	0.01251	0.01250	0.01190	F
5	Y	1.00002	1.00998	Y	1.01197	0.00005	0.01200	0.01250	0.01190	P

Suppose now that we are using LVDT #2 as the instrument. The accuracy of LVDT #2 is ±0.020 microns; the tolerance zone is ±0.5 microns. The TAR is 25:1. Because the TAR is ≥ 4:1, the measurement is accepted "as-read," and measurements within the tolerance zone are accepted as "Pass." Table 6-3 shows the same artificial data set as used in Table 6-2, but used with LVDT #2 as the instrument. Note the upper limit and lower limit are now the full specified limits of the material. Sample #4 that failed in Table 6-2 passes in Table 6-3.

Table 6-3: Measurement worksheet using artificial data with LVDT #2, 11 mm contact radius, 0.12 N force.

Standards used:										
LVDT#2			Exp: ww.ww.wwww							
Gage block set s/n ####			Exp: vv.vv.vvvv							
Film s/n:		Test only								
Operator:		*I.M. Technologist*								
Date/time:		*mm/dd/yyyy 10:15am*								
Environment meets specs?			*Yes*							
Sample #	Set 0?	1.000 mm block	1.010 mm block	OK to continue? (read ±0.000020 mm)	Film on top of 1.000 mm	Deformation corr (mm)	Film thickness (mm)	Upper limit (mm)	Lower limit (mm)	Pass/Fail?
1	Y	1.000010	1.010000	Y	1.012200	0.000054	0.012244	0.012700	0.011700	P
2	Y	1.000015	1.010018	Y	1.011940	0.000054	0.011979	0.012700	0.011700	P
3	Y	1.000000	1.010000	Y	1.012350	0.000054	0.012404	0.012700	0.011700	P
4	Y	0.999990	1.010010	Y	1.012450	0.000054	0.012514	0.012700	0.011700	P
5	Y	1.000018	1.009984	Y	1.011970	0.000054	0.012006	0.012700	0.011700	P

When making decisions for selecting measurement and test equipment, and developing procedures for making measurements that can affect the quality of a product or service delivered by Sandia, the user is encouraged to consult with the Primary Standards Laboratory. ASTM D374-99 (2004) provides other guidance for the measurement procedures, measuring single and stacked layers, and reporting requirements. It is strongly recommended that these procedures be followed, but using corrections for indentation as reported in this paper.

7. Conclusions

When using a micrometer with a spherical probe and flat anvil for measuring the thickness of a 48 gauge sheet of Mylar, the correction factor defined in ASTM D374-99 (2004) for probe indentation into the Mylar sample is inaccurate because it assumes the sample is a semi-infinite elastic solid as opposed to a thin sheet. This report has presented finite-element results predicting the correct indentation of a 12.2 micron thick Mylar sheet across a range of sphere radii and loads.

To minimize the effect of indentation into the sample a large sphere should be used at the lowest practical force level achievable by the measurement tool. It is left up to the user to determine that the force is sufficient to ensure the film sheet or stack is compressed flat against the anvil with no gaps or voids. In the limit of zero force this cannot be assured. As an example, for the case of an 11 mm radius sphere with 0.1 N applied load, the total indentation is only 0.085 microns. The correction for deformation compared to the zero reading is (0.085 – 0.035) microns = 0.050 micron (deformation into Mylar minus deformation into steel). This correction level may be insignificant with respect to the acceptance zone for product. If it is necessary to correct for the deformation of the Mylar film during measurement, then the appropriate correction can be obtained by using Eq. 12, with the individual deformations found using Eq. 4 and 5.

8. References

[1] Mylar® Polyester Film, Product Information, Physical-Thermal Properties, DuPont Teijin Films, June 2003.

[2] ASTM E252-99 (2006) "Standard Test Method for Thickness of Foil, Thin Sheet, and Film by Mass Measurement" 2006.

[3] C.-P. Anthony Liu and P. Neogi "Sorption of Methylene Chloride in Polyethylene Terephthalate," Journal of Applied Polymer Science, Vol. 35, 21-27, 1988.

[4] ASTM D374-99 (2004) "Standard Test Methods for Thickness of Solid Electrical Insulation", 2004.

[5] S.P. Timoshenko and J.N. Goodier, *Theory of Elasticity*, Third edition, McGraw-Hill Publishing Company, New York, 1987, pp. 409-414.

[6] M. M. Puttock and E.G. Thwaite, *Elastic Compression of Spheres and Cylinders at Point and Line Contact*, Technical Paper Number 25, Commonwealth Scientific and Industrial Research Organization Australia, 1969

[7] Mylar® C, Product Description, DuPont Teijin Films, http://www.dupontteijinfilms.com/filmenterprise/Datasheet.asp?Result=Print&ID=310&Version=US, accessed December 16, 2011.
[8] "General Requirements per 9900000", Issue AP, Sandia Labs Image Management System, January 2005.
[9] *Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications*. ASME B89.7.3.1:2011
[10] *Evaluation of measurement data-Guide to the expression of uncertainty in measurement*. JCGM 100:2008 (GUM 1995 with minor corrections).
[11] B. N. Taylor and C. E. Kuyatt. *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*. NIST Technical Note 1297. 1994.

9. Appendix A – ANSYS input scripts

All of the ANSYS APDL input macros have been included in this appendix for full documentation and to allow these results to be easily reproduced.

9.1. Rigid ball on semi-infinite solid

```
FINISH
finish
/CLEAR,start
/TITLE,Ball on Semi-Infinite
/FILNAME,zzz_mylar,ON
/UIS,MSGPOP,3
/UIS,abort,off

!*************************************************************
! Inputs for geometry and loads
!*************************************************************
! Units are mks

rad=5e-3  ! radius of sphere (m)
len1=1e-3  ! inner most mesh area size
len2=2.5e-3  ! size of middle mesh area from zero
len3=30e-3  ! radius and thickness of semi-infinite solid

yMod=5e9  ! Modulus (Pa)
pRat=0.38  ! poisson's ratio
frict=0   ! coefficient of friction

fMax=-1  ! force applied (N)

elemSize=10e-6  ! element size (m)
scale1=5   ! factor times element size to grow in middle mesh area
scale2=8   ! factor times middle size to grow for outer size mesh area

numSteps=10  ! number of load steps
fkn=100  ! contact stiffness

!*************************************************************
! End of User Configuration
!*************************************************************

/prep7
EMUNIT,EPZRO,8.85399999845E-06
PI=3.14159265359
*afun,deg

! Create geometry
blc4,0,0,len1,-len1
blc4,0,0,len2,-len2
blc4,0,0,len3,-len3
aovlap,all
asel,s,loc,x,len1/2
asel,r,loc,y,-len1/2
*get,a1,area,0,num,max
asel,s,loc,x,0,len2
```

```
asel,r,loc,y,0,-len2
asel,u,,,a1
*get,a2,area,0,num,max
asel,s,,,all
asel,u,,,a1
asel,u,,,a2
*get,a3,area,0,num,max
allsel,all

! Create contact sphere
*get,kpNum,kp,0,num,max
k,kpNum+1,0,0,0
k,kpNum+2,rad,rad,0
k,kpNum+3,0,rad,0
larc,kpNum+1,kpNum+2,kpNum+3,rad
pkp=kpNum+3

! Define structural elements
et,1,PLANE183
keyopt,1,3,1 ! axisymmetric

! Define contact elements
et,2,targe169
et,3,conta172
keyopt,3,1,0
keyopt,3,10,2 ! update stiffness each iteration
keyopt,3,12,0 ! friction.  0=set by material, 1=rough, infinite
keyopt,3,5,3  ! close gap or reduce initial penetration with auto CNOF
r,2,,,fkn

! Define material properties
mp,ex,1,yMod
mp,prxy,1,pRat
mp,mu,1,frict

! Mesh areas
type,1
mat,1
real,1
esize,elemSize
amesh,a1
esize,elemSize*scale1
amesh,a2
esize,elemSize*scale1*scale2
amesh,a3

! Mesh contacts
allsel,all
allsel,below,area
lsel,inve
type,2
real,2
lmesh,all
allsel,all
kmesh,pkp
ksel,s,,,pkp
nslk,s
```

```
*get,pNode,node,0,num,max
allsel,all
lsel,s,loc,y,0
lsel,r,loc,x,0,len1
type,3
lmesh,all

! Add constraints
lsel,s,loc,x,0
dl,all,,ux,0
lsel,s,loc,y,-len3
dl,all,,uy,0
allsel,all
d,pNode,ux,0
d,pNode,rotz,0
f,pNode,fy,fMax

! run solution
finish
/solu

antype,static
*if, numSteps,gt,0,then
   nlgeom,on
   nsubst,numSteps,numSteps*20,numSteps
   outres,all,all
   CNVTOL,U,,0.01,,0.02    ! *** Convergence for Displacement
   CNVTOL,F,,0.001,,0.002    ! *** Convergence for Force
*endif

allsel,all  ! always do this before a solve
solve

finish
/post1

! Get force displacement curve
*get,numSets,active,0,set,nset
set,first
*dim,resArray,array,numSets,2
*do,i,1,numSets
   *get,curTime,active,0,set,time
   appForce=curTime*fMax
   *get,disp,node,pNode,u,y
   resArray(i,1)=-appForce
   resArray(i,2)=-disp
   set,next
*enddo
/OUTPUT,results_force_disp,txt
*VWRITE,'force_N','disp_m'
%15s %15s
*VWRITE,resArray(1,1), resArray(1,2)
%15e %15e
/output

set,last
plnsol,u,sum
```

9.2. Thin Mylar on rigid anvil

```
FINISH
finish
/CLEAR,start
/TITLE,Mylar Thickness Test
/FILNAME,zzz_mylar,ON
/UIS,MSGPOP,3
/UIS,abort,off

!*****************************************************************
! Inputs for geometry and loads
!*****************************************************************

! Units are mks

rad=1.6e-3  ! radius of sphere (m)
thick=12.2e-6  ! thickness of sheet  (m)
len1=0.8e-3  ! length of material with elemSize (m)
len2=1.5e-3  ! total length with elemSize*scale1
len3=5e-3  ! total length with scale2

yMod=5e9  ! Modulus (Pa)
pRat=0.38
frict=0
slip=0 ! 0=no slip, 1=slip, between mylar and rigid anvil.

fMax=-1 ! force applied (N)

elemSize=5e-6  ! element size (m)
scale1=2  ! scale times element size for len2
scale2=2  ! scale times len2 size for len3

numSteps=10  ! number of load steps
fkn=100  ! contact stiffness

!*****************************************************************
! End of User Configuration
!*****************************************************************

/prep7
EMUNIT,EPZRO,8.85399999845E-06
PI=3.14159265359
*afun,deg

! Create geometry
blc4,0,0,len1,-thick
blc4,len1,0,len2-len1,-thick
blc4,len2,0,len3-len2,-thick
aglue,all
asel,s,loc,x,len1/2
*get,a1,area,0,num,max
asel,s,loc,x,(len1+len2)/2
*get,a2,area,0,num,max
asel,s,loc,x,(len2+len3)/2
*get,a3,area,0,num,max
allsel,all
```

```
! Create contact sphere
*get,kpNum,kp,0,num,max
k,kpNum+1,0,0,0
k,kpNum+2,rad,rad,0
k,kpNum+3,0,rad,0
larc,kpNum+1,kpNum+2,kpNum+3,rad
pkp=kpNum+3

! Define structural elements
et,1,PLANE183
keyopt,1,3,1 ! axisymmetric

! Define contact elements
et,2,targe169
et,3,conta172
keyopt,3,1,0
keyopt,3,10,2 ! update stiffness each iteration
keyopt,3,12,0 ! friction.  0=set by material, 1=rough, infinite
keyopt,3,5,3  ! close gap or reduce initial penetration with auto CNOF
r,2,,,fkn

! Define material properties
mp,ex,1,yMod
mp,prxy,1,pRat
mp,mu,1,frict

! Mesh areas
type,1
mat,1
real,1
esize,elemSize
amesh,a1
esize,elemSize*scale1
amesh,a2
esize,elemSize*scale1*scale2
amesh,a3

! Mesh contacts
allsel,all
allsel,below,area
lsel,inve
type,2
real,2
lmesh,all
allsel,all
kmesh,pkp
ksel,s,,,pkp
nslk,s
*get,pNode,node,0,num,max
allsel,all
lsel,s,loc,y,0
type,3
lmesh,all

! Add constraints
lsel,s,loc,x,0
```

```
dl,all,,ux,0
lsel,s,loc,y,-thick
dl,all,,uy,0
*if,slip,eq,0,then
   dl,all,,ux,0  ! no slip constraint.
*endif
allsel,all
d,pNode,ux,0
d,pNode,rotz,0
f,pNode,fy,fMax

! run solution
finish
/solu

antype,static
*if, numSteps,gt,0,then
   nlgeom,on
   nsubst,numSteps,numSteps*20,numSteps
   outres,all,all
   CNVTOL,U,,0.01,,0.02    ! *** Convergence for Displacement
   CNVTOL,F,,0.001,,0.002    ! *** Convergence for Force
*endif

allsel,all  ! always do this before a solve
solve

finish
/post1

! Get force displacement curve
*get,numSets,active,0,set,nset
set,first
*dim,resArray,array,numSets,2
*do,i,1,numSets
   *get,curTime,active,0,set,time
   appForce=curTime*fMax
   *get,disp,node,pNode,u,y
   resArray(i,1)=-appForce
   resArray(i,2)=-disp
   set,next
*enddo
/OUTPUT,results_force_disp,txt
*VWRITE,'force_N','disp_m'
%15s %15s
*VWRITE,resArray(1,1), resArray(1,2)
%15e %15e
/output

set,last
plnsol,u,sum
```

9.3. Thin Mylar on elastic anvil – no slip

```
FINISH
finish
/CLEAR,start
```

```
/TITLE,Single Mylar on Metal No Slip
/FILNAME,zzz_mylar,ON
/UIS,MSGPOP,3
/UIS,abort,off

!*****************************************************************
! Inputs for geometry and loads
!*****************************************************************

! Units are mks

rad=5e-3  ! radius of sphere (m)
len1=0.3e-3  ! inner most mesh area size
len2=0.6e-3  ! size of middle mesh area from zero
len3=10e-3  ! radius and thickness of semi-infinite solid

thick=12.2e-6  ! thickness of sheet  (m)

yModFilm=5e9  ! Modulus (Pa)
pRatFilm=0.38  ! poisson's ratio

yModBase=200e9  ! Modulus (Pa) of base metal
pRatBase=0.3  ! poisson ratio of base

frict=0   ! coefficient of friction

fMax=1  ! force applied (N)

elemSize=3e-6  ! element size (m)
scale1=5   ! factor times element size to grow in middle mesh area
scale2=8   ! factor times middle size to grow for outer size mesh area

numSteps=10  ! number of load steps
fkn=100  ! contact stiffness

!*****************************************************************
! End of User Configuration
!*****************************************************************

/prep7
EMUNIT,EPZRO,8.85399999845E-06
PI=3.14159265359
*afun,deg

! Create geometry
blc4,0,0,len1,-len1
blc4,0,0,len2,-len2
blc4,0,0,len3,-len3
blc4,0,0,len1,thick
blc4,0,0,len2,thick
blc4,0,0,len3,thick
aovlap,all
! Select each area for meshing
asel,s,loc,x,len1/2
asel,r,loc,y,-len1/2
*get,a1,area,0,num,max
asel,s,loc,x,0,len2
```

```
asel,r,loc,y,0,-len2
asel,u,,,a1
*get,a2,area,0,num,max
asel,s,loc,x,0,len3
asel,r,loc,y,0,-len3
asel,u,,,a1
asel,u,,,a2
*get,a3,area,0,num,max
! Select each film area
asel,s,loc,x,len1/2
*get,f1,area,0,num,max
asel,s,loc,x,(len1+len2)/2
*get,f2,area,0,num,max
asel,s,loc,x,(len2+len3)/2
*get,f3,area,0,num,max
allsel,all

! Create contact sphere
*get,kpNum,kp,0,num,max
k,kpNum+1,0,thick,0
k,kpNum+2,rad,rad+thick,0
k,kpNum+3,0,rad+thick,0
larc,kpNum+1,kpNum+2,kpNum+3,rad
pkp=kpNum+3

! Define structural elements
et,1,PLANE183
keyopt,1,3,1 ! axisymmetric

! Define contact elements
et,2,targe169
et,3,conta172
keyopt,3,1,0  ! UX UY DOF
keyopt,3,10,2 ! update stiffness each iteration
keyopt,3,12,0 ! friction.  0=set by material, 1=rough, infinite
keyopt,3,5,3  ! close gap or reduce initial penetration with auto CNOF
r,2,,,fkn

! Define material properties
mp,ex,1,yModFilm
mp,prxy,1,pRatFilm
mp,mu,1,frict

mp,ex,2,yModBase
mp,prxy,2,pRatBase
mp,mu,2,frict

! Mesh film areas
type,1
mat,1
real,1
esize,elemSize
amesh,f1
esize,elemSize*scale1
amesh,f2
esize,elemSize*scale1*scale2
amesh,f3
```

```
! Mesh base areas
mat,2
real,1
esize,elemSize
amesh,a1
esize,elemSize*scale1
amesh,a2
esize,elemSize*scale1*scale2
amesh,a3

! Mesh contacts
allsel,all
allsel,below,area
lsel,inve
type,2
real,2
lmesh,all
allsel,all
kmesh,pkp
ksel,s,,,pkp
nslk,s
*get,pNode,node,0,num,max
allsel,all
lsel,s,loc,y,thick
lsel,r,loc,x,0,len1
type,3
lmesh,all

! Add constraints
lsel,s,loc,x,0
dl,all,,ux,0
lsel,s,loc,y,-len3
dl,all,,uy,0
allsel,all
d,pNode,ux,0
d,pNode,rotz,0
f,pNode,fy,-fMax

! run solution
finish
/solu

antype,static
*if, numSteps,gt,0,then
   nlgeom,on
   nsubst,numSteps,numSteps*20,numSteps
   outres,all,all
   CNVTOL,U,,0.01,,0.02    ! *** Convergence for Displacement
   CNVTOL,F,,0.001,,0.002    ! *** Convergence for Force
*endif

allsel,all  ! always do this before a solve
solve

finish
/post1
```

```
! Get force displacement curve
*get,numSets,active,0,set,nset
set,first
*dim,resArray,array,numSets,2
*do,i,1,numSets
   *get,curTime,active,0,set,time
   appForce=curTime*fMax
   *get,disp,node,pNode,u,y
   resArray(i,1)=appForce
   resArray(i,2)=-disp
   set,next
*enddo
/OUTPUT,results_force_disp,txt
*VWRITE,'force_N','disp_m'
%15s %15s
*VWRITE,resArray(1,1), resArray(1,2)
%15e %15e
/output

set,last
/NUMBER,1
/PNUM,MAT,1
plnsol,u,sum
```

9.4. Thin Mylar on elastic anvil – with slip

```
FINISH
finish
/CLEAR,start
/TITLE,Single Mylar on Metal With Slip
/FILNAME,zzz_mylar,ON
/UIS,MSGPOP,3
/UIS,abort,off

!*****************************************************************
! Inputs for geometry and loads
!*****************************************************************

! Units are mks

rad=5e-3  ! radius of sphere (m)
len1=0.3e-3  ! inner most mesh area size
len2=0.6e-3  ! size of middle mesh area from zero
len3=10e-3  ! radius and thickness of semi-infinite solid

thick=12.2e-6  ! thickness of sheet  (m)

yModFilm=5e9  ! Modulus (Pa)
pRatFilm=0.38  ! poisson's ratio

yModBase=200e9  ! Modulus (Pa) of base metal
pRatBase=0.3  ! poisson ratio of base

frict=0   ! coefficient of friction

fMax=1  ! force applied (N)
```

```
elemSize=3e-6  ! element size (m)
scale1=5   ! factor times element size to grow in middle mesh area
scale2=8   ! factor times middle size to grow for outer size mesh area

numSteps=10  ! number of load steps
fkn=100  ! contact stiffness
fknFilm=100  ! contact stiffness for film contact

!*****************************************************************
! End of User Configuration
!*****************************************************************

/prep7
EMUNIT,EPZRO,8.85399999845E-06
PI=3.14159265359
*afun,deg

! Create geometry
blc4,0,0,len1,-len1
blc4,0,0,len2,-len2
blc4,0,0,len3,-len3
aovlap,all
asel,u,,,all
blc4,0,0,len1,thick
blc4,0,0,len2,thick
blc4,0,0,len3,thick
aovlap,all
! Select each area for meshing
asel,s,loc,x,len1/2
asel,r,loc,y,-len1/2
*get,a1,area,0,num,max
asel,s,loc,x,0,len2
asel,r,loc,y,0,-len2
asel,u,,,a1
*get,a2,area,0,num,max
asel,s,loc,x,0,len3
asel,r,loc,y,0,-len3
asel,u,,,a1
asel,u,,,a2
*get,a3,area,0,num,max
! Select each film area
asel,s,loc,x,len1/2
*get,f1,area,0,num,max
asel,s,loc,x,(len1+len2)/2
*get,f2,area,0,num,max
asel,s,loc,x,(len2+len3)/2
*get,f3,area,0,num,max
allsel,all

! Create contact sphere
*get,kpNum,kp,0,num,max
k,kpNum+1,0,thick,0
k,kpNum+2,rad,rad+thick,0
k,kpNum+3,0,rad+thick,0
larc,kpNum+1,kpNum+2,kpNum+3,rad
pkp=kpNum+3
```

```
! Define structural elements
et,1,PLANE183
keyopt,1,3,1 ! axisymmetric

! Define contact elements
et,2,targe169
et,3,conta172
keyopt,3,1,0  ! UX UY DOF
keyopt,3,10,2 ! update stiffness each iteration
keyopt,3,12,0 ! friction.  0=set by material, 1=rough, infinite
keyopt,3,5,3  ! close gap or reduce initial penetration with auto CNOF
et,4,conta172
keyopt,4,1,0  ! UX UY DOF
keyopt,4,10,2 ! update stiffness each iteration
keyopt,4,12,2 ! friction.  0=set by material, 1=rough, infinite, 2=bonded
with sliding
keyopt,4,5,3  ! close gap or reduce initial penetration with auto CNOF

r,2,,,fkn
r,3,,,fknFilm

! Define material properties
mp,ex,1,yModFilm
mp,prxy,1,pRatFilm
mp,mu,1,frict

mp,ex,2,yModBase
mp,prxy,2,pRatBase
mp,mu,2,frict

! Mesh film areas
type,1
mat,1
real,1
esize,elemSize
amesh,f1
esize,elemSize*scale1
amesh,f2
esize,elemSize*scale1*scale2
amesh,f3

! Mesh base areas
mat,2
real,1
esize,elemSize
amesh,a1
esize,elemSize*scale1
amesh,a2
esize,elemSize*scale1*scale2
amesh,a3

! Mesh ball contacts
allsel,all
allsel,below,area
lsel,inve
type,2
```

```
real,2
lmesh,all
allsel,all
kmesh,pkp
ksel,s,,,pkp
nslk,s
*get,pNode,node,0,num,max
allsel,all
asel,s,,,f1
allsel,below,area
lsel,r,loc,y,thick
lsel,r,loc,x,0,len1
type,3
lmesh,all

! Mesh layer contact
real,3
type,2
asel,s,loc,y,-len3,0
allsel,below,area
lsel,r,loc,y,0
nsll,s
esln,s
esurf
!lmesh,all
type,4
asel,s,loc,y,0,thick
allsel,below,area
lsel,r,loc,y,0
nsll,s
esln,s
esurf
!lmesh,all

! Add constraints
lsel,s,loc,x,0
dl,all,,ux,0
lsel,s,loc,y,-len3
dl,all,,uy,0
allsel,all
d,pNode,ux,0
d,pNode,rotz,0
f,pNode,fy,-fMax

! run solution
finish
/solu

antype,static
*if, numSteps,gt,0,then
   nlgeom,on
   nsubst,numSteps,numSteps*20,numSteps
   outres,all,all
   CNVTOL,U,,0.01,,0.02    ! *** Convergence for Displacement
   CNVTOL,F,,0.001,,0.002    ! *** Convergence for Force ***
*endif
```

```
allsel,all  ! always do this before a solve
solve

finish
/post1

! Get force displacement curve
*get,numSets,active,0,set,nset
set,first
*dim,resArray,array,numSets,2
*do,i,1,numSets
   *get,curTime,active,0,set,time
   appForce=curTime*fMax
   *get,disp,node,pNode,u,y
   resArray(i,1)=appForce
   resArray(i,2)=-disp
   set,next
*enddo
/OUTPUT,results_force_disp,txt
*VWRITE,'force_N','disp_m'
%15s %15s
*VWRITE,resArray(1,1), resArray(1,2)
%15e %15e
/output

set,last
/NUMBER,1
/PNUM,MAT,1
plnsol,u,sum
```

9.5. Five stacked Mylar layers on compliant steel anvil – with Slip

```
FINISH
finish
/CLEAR,start
/TITLE,Single Mylar on Metal With Slip
/FILNAME,zzz_mylar,ON
/UIS,MSGPOP,3
/UIS,abort,off

!*****************************************************************
! Inputs for geometry and loads
!*****************************************************************

! Units are mks

rad=5e-3  ! radius of sphere (m)
len1=0.3e-3  ! inner most mesh area size
len2=0.6e-3  ! size of middle mesh area from zero
len3=10e-3  ! radius and thickness of semi-infinite solid

thick=12.2e-6  ! thickness of sheet  (m)

yModFilm=5e9  ! Modulus (Pa)
pRatFilm=0.38  ! poisson's ratio

yModBase=200e9  ! Modulus (Pa) of base metal
```

```
pRatBase=0.3  ! poisson ratio of base

frict=0   ! coefficient of friction

fMax=1  ! force applied (N)

elemSize=3e-6  ! element size (m)
scale1=5   ! factor times element size to grow in middle mesh area
scale2=8   ! factor times middle size to grow for outer size mesh area

numSteps=10  ! number of load steps
fkn=100  ! contact stiffness
fknFilm=100  ! contact stiffness for film contact

!*****************************************************************
! End of User Configuration
!*****************************************************************

/prep7
EMUNIT,EPZRO,8.85399999845E-06
PI=3.14159265359
*afun,deg

! Create geometry
blc4,0,0,len1,-len1
blc4,0,0,len2,-len2
blc4,0,0,len3,-len3
aovlap,all
asel,u,,,all
blc4,0,0,len1,thick
blc4,0,0,len2,thick
blc4,0,0,len3,thick
aovlap,all
asel,u,,,all
blc4,0,thick,len1,thick
blc4,0,thick,len2,thick
blc4,0,thick,len3,thick
aovlap,all
asel,u,,,all
blc4,0,2*thick,len1,thick
blc4,0,2*thick,len2,thick
blc4,0,2*thick,len3,thick
aovlap,all
asel,u,,,all
blc4,0,3*thick,len1,thick
blc4,0,3*thick,len2,thick
blc4,0,3*thick,len3,thick
aovlap,all
asel,u,,,all
blc4,0,4*thick,len1,thick
blc4,0,4*thick,len2,thick
blc4,0,4*thick,len3,thick
aovlap,all

! Select each area for meshing
asel,s,loc,x,len1/2
asel,r,loc,y,-len1/2
```

```
*get,a1,area,0,num,max
asel,s,loc,x,0,len2
asel,r,loc,y,0,-len2
asel,u,,,a1
*get,a2,area,0,num,max
asel,s,loc,x,0,len3
asel,r,loc,y,0,-len3
asel,u,,,a1
asel,u,,,a2
*get,a3,area,0,num,max

! Select each film area
asel,s,loc,y,0,thick
asel,r,loc,x,len1/2
*get,f1,area,0,num,max
asel,s,loc,y,0,thick
asel,r,loc,x,(len1+len2)/2
*get,f2,area,0,num,max
asel,s,loc,y,0,thick
asel,r,loc,x,(len2+len3)/2
*get,f3,area,0,num,max

asel,s,loc,y,thick,2*thick
asel,r,loc,x,len1/2
*get,f12,area,0,num,max
asel,s,loc,y,thick,2*thick
asel,r,loc,x,(len1+len2)/2
*get,f22,area,0,num,max
asel,s,loc,y,thick,2*thick
asel,r,loc,x,(len2+len3)/2
*get,f32,area,0,num,max

asel,s,loc,y,2*thick,3*thick
asel,r,loc,x,len1/2
*get,f13,area,0,num,max
asel,s,loc,y,2*thick,3*thick
asel,r,loc,x,(len1+len2)/2
*get,f23,area,0,num,max
asel,s,loc,y,2*thick,3*thick
asel,r,loc,x,(len2+len3)/2
*get,f33,area,0,num,max

asel,s,loc,y,3*thick,4*thick
asel,r,loc,x,len1/2
*get,f14,area,0,num,max
asel,s,loc,y,3*thick,4*thick
asel,r,loc,x,(len1+len2)/2
*get,f24,area,0,num,max
asel,s,loc,y,3*thick,4*thick
asel,r,loc,x,(len2+len3)/2
*get,f34,area,0,num,max

asel,s,loc,y,4*thick,5*thick
asel,r,loc,x,len1/2
*get,f15,area,0,num,max
asel,s,loc,y,4*thick,5*thick
asel,r,loc,x,(len1+len2)/2
```

```
*get,f25,area,0,num,max
asel,s,loc,y,4*thick,5*thick
asel,r,loc,x,(len2+len3)/2
*get,f35,area,0,num,max

allsel,all

! Create contact sphere
*get,kpNum,kp,0,num,max
k,kpNum+1,0,5*thick,0
k,kpNum+2,rad,rad+5*thick,0
k,kpNum+3,0,rad+5*thick,0
larc,kpNum+1,kpNum+2,kpNum+3,rad
pkp=kpNum+3

! Define structural elements
et,1,PLANE183
keyopt,1,3,1 ! axisymmetric

! Define contact elements
et,2,targe169
et,3,conta172
keyopt,3,1,0  ! UX UY DOF
keyopt,3,10,2 ! update stiffness each iteration
keyopt,3,12,0 ! friction.  0=set by material, 1=rough, infinite
keyopt,3,5,3  ! close gap or reduce initial penetration with auto CNOF
et,4,conta172
keyopt,4,1,0  ! UX UY DOF
keyopt,4,10,2 ! update stiffness each iteration
keyopt,4,12,2 ! friction.  0=set by material, 1=rough, infinite, 2=bonded
with sliding
keyopt,4,5,3  ! close gap or reduce initial penetration with auto CNOF

r,2,,,fkn
r,3,,,fknFilm
r,4,,,fknFilm
r,5,,,fknFilm
r,6,,,fknFilm
r,7,,,fknFilm

! Define material properties
mp,ex,1,yModFilm
mp,prxy,1,pRatFilm
mp,mu,1,frict

mp,ex,2,yModBase
mp,prxy,2,pRatBase
mp,mu,2,frict

! Mesh film areas
type,1
mat,1
real,1
esize,elemSize
amesh,f1
amesh,f12
amesh,f13
```

```
amesh,f14
amesh,f15
esize,elemSize*scale1
amesh,f2
amesh,f22
amesh,f23
amesh,f24
amesh,f25
esize,elemSize*scale1*scale2
amesh,f3
amesh,f32
amesh,f33
amesh,f34
amesh,f35

! Mesh base areas
mat,2
real,1
esize,elemSize
amesh,a1
esize,elemSize*scale1
amesh,a2
esize,elemSize*scale1*scale2
amesh,a3

! Mesh ball contacts
allsel,all
allsel,below,area
lsel,inve
type,2
real,2
lmesh,all
allsel,all
kmesh,pkp
ksel,s,,,pkp
nslk,s
*get,pNode,node,0,num,max
allsel,all
asel,s,,,f15
allsel,below,area
lsel,r,loc,y,5*thick
lsel,r,loc,x,0,len1
type,3
nsll,s
esln,s
esurf
!lmesh,all

! Mesh layer contact
real,3
type,2
asel,s,loc,y,-len3,0
allsel,below,area
lsel,r,loc,y,0
nsll,s
esln,s
esurf
```

```
type,4
asel,s,loc,y,0,thick
allsel,below,area
lsel,r,loc,y,0
nsll,s
esln,s
esurf

real,4
type,2
asel,s,loc,y,0,thick
allsel,below,area
lsel,r,loc,y,thick
nsll,s
esln,s
esurf
type,4
asel,s,loc,y,thick,2*thick
allsel,below,area
lsel,r,loc,y,thick
nsll,s
esln,s
esurf

real,5
type,2
asel,s,loc,y,thick,2*thick
allsel,below,area
lsel,r,loc,y,2*thick
nsll,s
esln,s
esurf
type,4
asel,s,loc,y,2*thick,3*thick
allsel,below,area
lsel,r,loc,y,2*thick
nsll,s
esln,s
esurf

real,6
type,2
asel,s,loc,y,2*thick,3*thick
allsel,below,area
lsel,r,loc,y,3*thick
nsll,s
esln,s
esurf
type,4
asel,s,loc,y,3*thick,4*thick
allsel,below,area
lsel,r,loc,y,3*thick
nsll,s
esln,s
esurf

real,7
```

```
type,2
asel,s,loc,y,3*thick,4*thick
allsel,below,area
lsel,r,loc,y,4*thick
nsll,s
esln,s
esurf
type,4
asel,s,loc,y,4*thick,5*thick
allsel,below,area
lsel,r,loc,y,4*thick
nsll,s
esln,s
esurf

! Add constraints
lsel,s,loc,x,0
dl,all,,ux,0
lsel,s,loc,y,-len3
dl,all,,uy,0
allsel,all
d,pNode,ux,0
d,pNode,rotz,0
f,pNode,fy,-fMax

! run solution
finish
/solu

antype,static
*if, numSteps,gt,0,then
   nlgeom,on
   nsubst,numSteps,numSteps*20,numSteps
   outres,all,all
   CNVTOL,U,,0.01,,0.02    ! *** Convergence for Displacement ***  def.
0.05 and 0
   CNVTOL,F,,0.001,,0.002    ! *** Convergence for Force ***  def. 0.005
and 0.01
*endif

allsel,all  ! always do this before a solve
solve

finish
/post1

! Get force displacement curve
*get,numSets,active,0,set,nset
set,first
*dim,resArray,array,numSets,2
*do,i,1,numSets
   *get,curTime,active,0,set,time
   appForce=curTime*fMax
   *get,disp,node,pNode,u,y
   resArray(i,1)=appForce
   resArray(i,2)=-disp
   set,next
```

```
*enddo
/OUTPUT,results_force_disp,txt
*VWRITE,'force_N','disp_m'
%15s %15s
*VWRITE,resArray(1,1), resArray(1,2)
%15e %15e
/output

set,last
/NUMBER,1
/PNUM,MAT,1
plnsol,u,sum
```

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