Designation: E2245 – 05

Standard Test Method for
Residual Strain Measurements of Thin, Reflecting Films Using an Optical Interferometer[1]

This standard is issued under the fixed designation E2245; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers a procedure for measuring the compressive residual strain in thin films. It applies only to films, such as found in microelectromechanical systems (MEMS) materials, which can be imaged using an optical interferometer. Measurements from fixed-fixed beams that are touching the underlying layer are not accepted.

1.2 This test method uses a non-contact optical interferometer with the capability of obtaining topographical 3-D data sets. It is performed in the laboratory.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E2244 Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer

E2246 Test Method for Strain Gradient Measurements of Thin, Reflecting Films Using an Optical Interferometer

3. Terminology

3.1 *Definitions:*

3.1.1 *2-D data trace*, *n*—a two-dimensional group of points that is extracted from a topographical 3-D data set and that is parallel to the *xz*- or *yz*-plane of the interferometer.

3.1.2 *3-D data set*, *n*—a three-dimensional group of points with a topographical *z*-value for each (*x*, *y*) pixel location within the interferometer's field of view.

3.1.3 *anchor*, *n*—in a surface-micromachining process, the portion of the test structure where a structural layer is intentionally attached to its underlying layer.

3.1.4 *anchor lip*, *n*—in a surface-micromachining process, the freestanding extension of the structural layer of interest around the edges of the anchor to its underlying layer.

3.1.4.1 *Discussion*—In some processes, the width of the anchor lip may be zero.

3.1.5 *bulk micromachining*, *adj*—a MEMS fabrication process where the substrate is removed at specified locations.

3.1.6 *cantilever*, *n*—a test structure that consists of a freestanding beam that is fixed at one end.

3.1.7 *fixed-fixed beam*, *n*—a test structure that consists of a freestanding beam that is fixed at both ends.

3.1.8 *in-plane length (or deflection) measurement*, *n*—the experimental determination of the straight-line distance between two transitional edges in a MEMS device.

3.1.8.1 *Discussion*—This length (or deflection) measurement is made parallel to the underlying layer (or the *xy*-plane of the interferometer).

3.1.9 *interferometer*, *n*—a non-contact optical instrument used to obtain topographical 3-D data sets.

3.1.9.1 *Discussion*—The height of the sample is measured along the *z*-axis of the interferometer. The interferometer's *x*-axis is typically aligned parallel or perpendicular to the transitional edges to be measured.

3.1.10 *MEMS*, *adj*—microelectromechanical system.

3.1.11 *microelectromechanical systems*, *adj*—in general, this term is used to describe micron-scale structures, sensors, actuators or the technologies used for their manufacture (such as, silicon process technologies), or combinations thereof.

3.1.12 *out-of-plane measurements*, *n*—experimental data taken on structures that are curved in the interferometer's *z*-direction (that is, perpendicular to the underlying layer).

3.1.13 *residual strain*, *n*—in a MEMS process, the amount of deformation (or displacement) per unit length constrained within the structural layer of interest after fabrication yet before the constraint of the sacrificial layer (or substrate) is removed (in whole or in part).

3.1.14 *sacrificial layer*, *n*—a single thickness of material that is intentionally deposited (or added) then removed (in whole or in part) during the micromachining process, to allow freestanding microstructures.

3.1.15 *stiction*, *n*—adhesion between the portion of a structural layer that is intended to be freestanding and its underlying layer.

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[1] This test method is under the jurisdiction of ASTM Committee E08 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.05 on Cyclic Deformation and Fatigue Crack Formation.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.1.16 *(residual) strain gradient*, *n*—a through-thickness variation (of the residual strain) in the structural layer of interest before it is released.

3.1.16.1 *Discussion*—If the variation through the thickness in the structural layer is assumed to be linear, it is calculated to be the positive difference in the residual strain between the top and bottom of a cantilever divided by its thickness. Directional information is assigned to the value of "s."

3.1.17 *structural layer*, *n*—a single thickness of material present in the final MEMS device.

3.1.18 *substrate*, *n*—the thick, starting material (often single crystal silicon or glass) in a fabrication process that can be used to build MEMS devices.

3.1.19 *support region*, *n*—in a bulk-micromachining process, the area that marks the end of the suspended structure.

3.1.20 *surface micromachining*, *adj*—a MEMS fabrication process where micron-scale components are formed on a substrate by the deposition (or addition) and removal (in whole or in part) of structural and sacrificial layers.

3.1.21 *test structure*, *n*—a component (such as, a fixed-fixed beam or cantilever) that is used to extract information (such as, the residual strain or the strain gradient of a layer) about a fabrication process.

3.1.22 *transitional edge*, *n*—the side of a MEMS structure that is characterized by a distinctive out-of-plane vertical displacement as seen in an interferometric 2-D data trace.

3.1.23 *underlying layer*, *n*—the single thickness of material directly beneath the material of interest.

3.1.23.1 *Discussion*—This layer could be the substrate.

3.2 *Symbols:*

3.2.1 *For Calibration*:

σ_{xcal} = the standard deviation in a ruler measurement in the interferometer's *x*-direction for the given combination of lenses

σ_{ycal} = the standard deviation in a ruler measurement in the interferometer's *y*-direction for the given combination of lenses

σ_{zcal} = the standard deviation of the step height measurements on the double-sided step height standard

cal_x = the *x*-calibration factor of the interferometer for the given combination of lenses

cal_y = the *y*-calibration factor of the interferometer for the given combination of lenses

cal_z = the *z*-calibration factor of the interferometer for the given combination of lenses

$cert$ = the certified value of the double-sided step height standard

$inter_x$ = the interferometer's maximum field of view in the *x*-direction for the given combination of lenses

$inter_y$ = the interferometer's maximum field of view in the *y*-direction for the given combination of lenses

$mean$ = the mean value of the step-height measurements (on the double-sided step height standard) used to calculate cal_z

$ruler_x$ = the interferometer's maximum field of view in the *x*-direction for the given combination of lenses as measured with a 10-μm grid (or finer grid) ruler

$ruler_y$ = the interferometer's maximum field of view in the *y*-direction for the given combination of lenses as measured with a 10-μm grid (or finer grid) ruler

3.2.2 *For Alignment*:

$x1_{lower}$ = the *x*-data value along Edge "1" locating the lower part of the transitional edge

$x1_{upper}$ = the *x*-data value along Edge "1" locating the upper part of the transitional edge

$x2_{lower}$ = the *x*-data value along Edge "2" locating the lower part of the transitional edge

$x2_{upper}$ = the *x*-data value along Edge "2" locating the upper part of the transitional edge

x_{lower} = the *x*-data value along the transitional edge of interest locating the lower part of the transition

x_{upper} = the *x*-data value along the transitional edge of interest locating the upper part of the transition

3.2.3 *For In-plane Length Measurement*:

L = the in-plane length measurement of the fixed-fixed beam

L_{max} = the maximum in-plane length measurement of the fixed-fixed beam

L_{min} = the minimum in-plane length measurement of the fixed-fixed beam

$x1_{ave}$ = an endpoint of the in-plane length measurement (that is, the average of $x1_{min}$ and $x1_{max}$)

$x1_{max}$ = the value for $x1_{upper}$ used in the calculation of L_{max}

$x1_{min}$ = the value for $x1_{lower}$ used in the calculation of L_{min}

$x2_{ave}$ = the other endpoint of the in-plane length measurement (that is, the average of $x2_{min}$ and $x2_{max}$)

$x2_{max}$ = the value for $x2_{upper}$ used in the calculation of L_{max}

$x2_{min}$ = the value for $x2_{lower}$ used in the calculation of L_{min}

3.2.4 *For Residual Strain Measurement*:

ε_r = the residual strain

A_F = the amplitude of the cosine function used to model the first abbreviated data trace (or curve #1)

A_S = the amplitude of the cosine function used to model the second abbreviated data trace (or curve #2)

L_0 = the length of the fixed-fixed beam if there were no applied axial-compressive force

L_c = the total length of the curved fixed-fixed beam (as modeled with two cosine functions) with $x1_{ave}$ and $x2_{ave}$ as the *x* values of the endpoints

L_{cF} = the length of the cosine function modeling the first curve (or curve #1) with $x1_{ave}$ and x_{3F} as the *x* values of the endpoints

L_{cS} = the length of the cosine function modeling the second curve (or curve #2) with x_{1S} and $x2_{ave}$ as the *x* values of the endpoints

L_e' = the effective length of the fixed-fixed beam. This is a straight-line measurement between x_{eF} and x_{eS}

s = equals 1 for fixed-fixed beams deflected in the minus *z*-direction of the interferometer, and equals −1 for fixed-fixed beams deflected in the plus *z*-direction

t = the thickness of the suspended, structural layer

$t_{support}$ = in a bulk-micromachining process, the thickness of the support region where it is intersected by the interferometric 2-D data trace of interest

x_{eF} = the *x* value of the inflection point of the cosine function modeling the first abbreviated data trace (or curve #1)

x_{eS} = the x value of the inflection point of the cosine function modeling the second abbreviated data trace (or curve #2)

z_{upper} = the z-data value associated with x_{upper}

$z_{upper\text{-}t}$ = in a bulk-micromachining process, the value for z when the thickness of the support region, $t_{support}$, is subtracted from z_{upper}

3.2.5 *For Combined Standard Uncertainty Calculations*:

$\varepsilon_{r\text{-}high}$ = in determining the combined standard uncertainty value for the residual strain measurement, the highest value for ε_r given the specified variations

$\varepsilon_{r\text{-}low}$ = in determining the combined standard uncertainty value for the residual strain measurement, the lowest value for ε_r given the specified variations

σ_{sample} = the standard deviation in a height measurement due to the sample's peak-to-valley surface roughness as measured with the interferometer

$L_{c\text{-}max}$ = the total length of the curved fixed-fixed beam (as modeled with two cosine functions) with $x1_{max}$ and $x2_{max}$ as the x values of the endpoints

$L_{c\text{-}min}$ = the total length of the curved fixed-fixed beam (as modeled with two cosine functions) with $x1_{min}$ and $x2_{min}$ as the x values of the endpoints

R_{tave} = the peak-to-valley roughness of a flat and leveled surface of the sample material calculated to be the average of three or more measurements, each measurement of which is taken from a different 2-D data trace

u_c = the combined standard uncertainty value (that is, the estimated standard deviation of the result)

u_L = the component in the combined standard uncertainty calculation for residual strain that is due to the measurement uncertainty of L

u_{samp} = the component in the combined standard uncertainty calculation for residual strain that is due to the sample's peak-to-valley surface roughness as measured with the interferometer

u_W = the component in the combined standard uncertainty calculation for residual strain that is due to the measurement uncertainty across the width of the fixed-fixed beam

u_{xcal} = the component in the combined standard uncertainty calculation for residual strain that is due to the uncertainty of the calibration in the x-direction

u_{xres} = the component in the combined standard uncertainty calculation for residual strain that is due to the resolution of the interferometer in the x-direction as pertains to the chosen data points along the fixed-fixed beam

u_{xresL} = the component in the combined standard uncertainty calculation for residual strain that is due to the resolution of the interferometer in the x-direction as pertains to the in-plane length measurement

u_{zcal} = the component in the combined standard uncertainty calculation for residual strain that is due to the uncertainty of the calibration in the z-direction

u_{zres} = the component in the combined standard uncertainty calculation for residual strain that is due to the resolution of the interferometer in the z-direction

$w_{1/2}$ = the half width of the interval from $\varepsilon_{r\text{-}low}$ to $\varepsilon_{r\text{-}high}$

x_{res} = the resolution of the interferometer in the x-direction

z_{res} = the resolution of the interferometer in the z-direction

3.2.6 *For Round Robin Measurements*:

ε_{rave} = the average residual strain value for the reproducibility or repeatability measurements. It is equal to the sum of the ε_r values divided by n.

L_{des} = the design length of the fixed-fixed beam

n = the number of reproducibility or repeatability measurements

u_{cave} = the average combined standard uncertainty value for the reproducibility or repeatability measurements. It is equal to the sum of the u_c values divided by n.

3.2.7 *For Adherence to the Top of the Underlying Layer*:

A = in a surface micromachining process, the minimum thickness of the structural layer of interest as measured from the top of the structural layer in the anchor area to the top of the underlying layer

H = in a surface micromachining process, the anchor etch depth, which is the amount the underlying layer is etched away in the interferometer's minus z-direction during the patterning of the sacrificial layer

J = in a surface micromachining process, the positive distance (equal to the sum of j_a, j_b, j_c, and j_d) between the bottom of the suspended, structural layer and the top of the underlying layer

j_a = in a surface micromachining process, half the peak-to-peak value of the roughness of the underside of the suspended, structural layer in the interferometer's z-direction. This is due to the roughness of the topside of the sacrificial layer.

j_b = in a surface micromachining process, the tilting component of the suspended, structural layer that accounts for the deviation in the distance between the bottom of the suspended, structural layer and the top of the underlying layer that is not due to residue or the roughness of the surfaces. This component can be positive or negative.

j_c = in a surface micromachining process, the height in the interferometer's z-direction of any residue present between the bottom of the suspended, structural layer and the top of the underlying layer

j_d = in a surface micromachining process, half the peak-to-peak value of the surface roughness of the topside of the underlying layer

$z_{reg\#1}$ = in a surface micromachining process, the interferometric z value of the point of maximum deflection along the fixed-fixed beam with respect to an anchor lip

$z_{reg\#2}$ = in a surface micromachining process, a representative interferometric z value of the group of points within the large anchor area

3.2.8 *Discussion*—The symbols above are used throughout this test method. However, when referring to y values, the letter "y" can replace the first letter in the symbols above that start with the letter "x."

4. Summary of Test Method

4.1 A fixed-fixed beam is shown in Figs. 1-3. After fabrication, this fixed-fixed beam bends in the out-of-plane z-direction. An optical interferometer (such as shown in Fig. 4) is used to obtain a topographical 3-D data set. Two-D data traces beside the fixed-fixed beam (such as shown in Fig. 5)

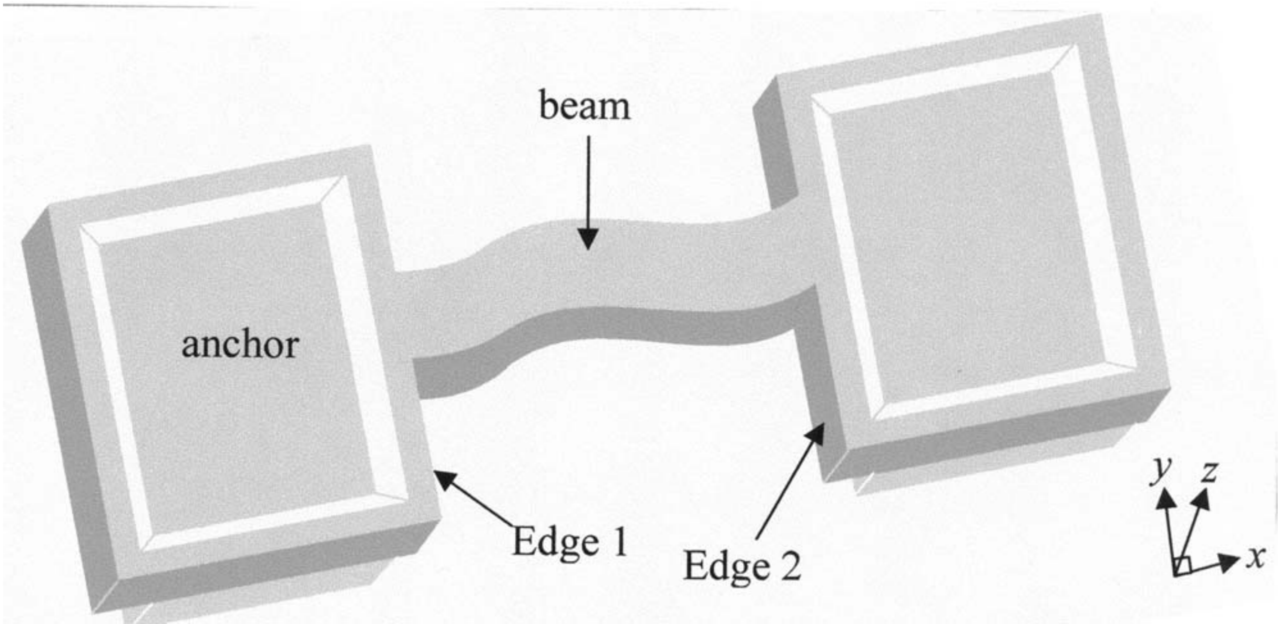
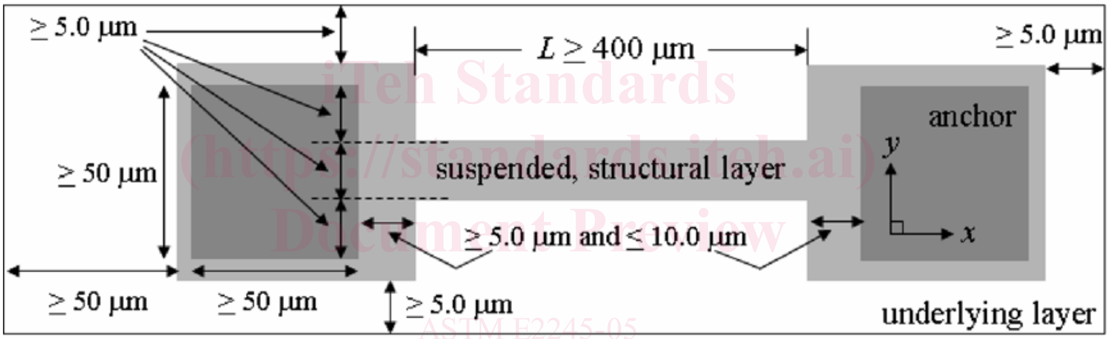


FIG. 1 Three-Dimensional View of Surface-Micromachined Fixed-Fixed Beam



NOTE 1—The underlying layer is beneath this test structure.
NOTE 2—The structural layer of interest is included in both the light and dark gray areas.
NOTE 3—The light gray area is suspended in air after fabrication.
NOTE 4—The dark gray areas (the anchors) are the designed cuts in the sacrificial layer. This is where the structural layer contacts the underlying layer.

FIG. 2 Design Dimensions for Fixed-Fixed Beam in Fig. 1

and along the top of the fixed-fixed beam (such as shown in Fig. 6) are extracted from this 3-D data set for the residual strain analysis.

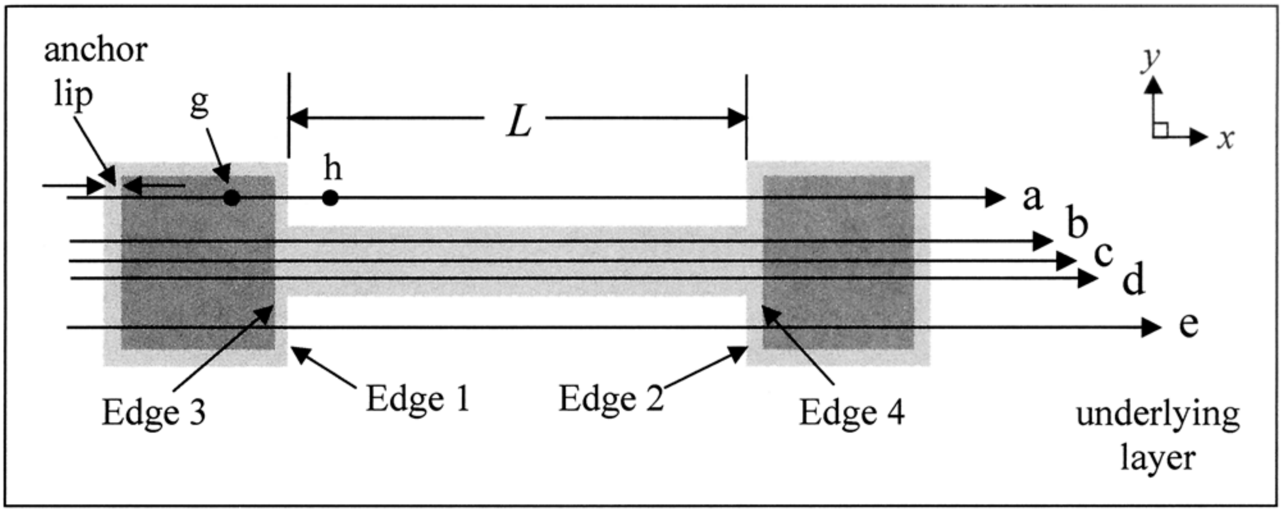
4.2 Two cosine functions model the out-of-plane shape of fixed-fixed beams. These functions are merged at the peak or valley deflection. Three data points are chosen to define each cosine function. The residual strain is calculated after the appropriate lengths are determined.

4.3 For a surface-micromachined fixed-fixed beam, to obtain three data points that define each cosine function: (*1*) select four transitional edges, (*2*) obtain a 3-D data set, (*3*) ensure alignment, (*4*) determine the endpoints of the in-plane length measurement, and (*5*) obtain three data points that define each cosine function. (This procedure is presented in Appendix X1 for a bulk-micromachined fixed-fixed beam or a surface-micromachined fixed-fixed beam with transitional edges greater than 8 µm in height.)

4.4 To calculate the residual strain: (*1*) solve three equations for three unknowns to obtain each cosine function, (*2*) plot the functions with the data, (*3*) calculate the length of the curved fixed-fixed beam, and (*4*) calculate the residual strain.

5. Significance and Use

5.1 Residual strain measurements are an aid in the design and fabrication of MEMS devices. The value for residual strain is used in Young's modulus calculations.



NOTE 1—The 2-D data traces (“a” and “e”) are used to ensure alignment and determine *L*.

NOTE 2—Trace “c” is used to determine the residual strain and ascertain if the fixed-fixed beam is adhered to the top of the underlying layer.

NOTE 3—Traces “b,” “c,” and “d” can be used in the calculation of u_W.

FIG. 3 Top View of Fixed-Fixed Beam

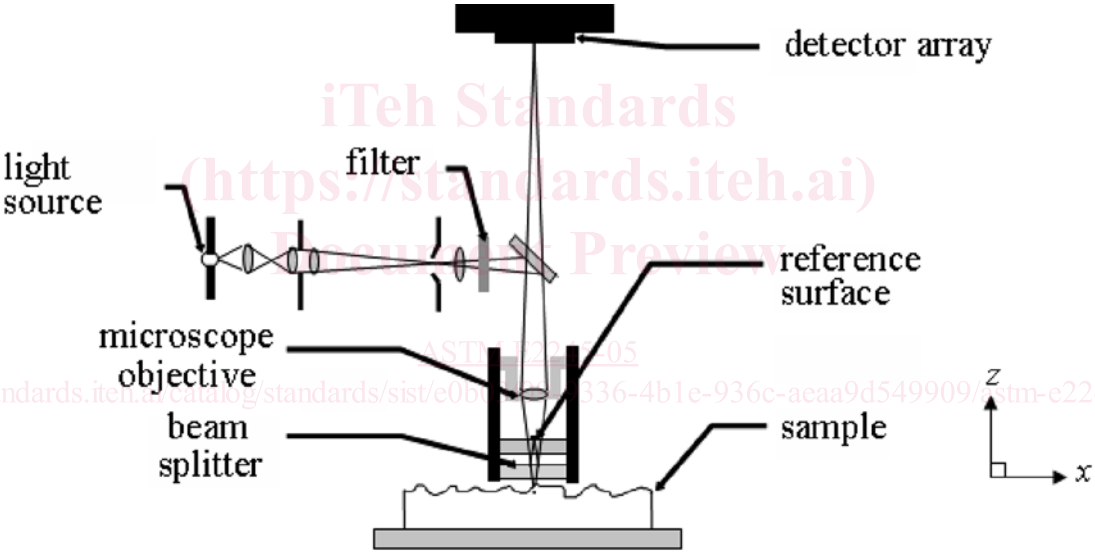


FIG. 4 Schematic of an Optical Interferometer

6. Interferences

6.1 Measurements from fixed-fixed beams that are touching the underlying layer (as ascertained in Appendix X2) are not accepted.

7. Apparatus (1) [3, 4]

7.1 *Non-contact Optical Interferometer*, capable of obtaining a topographical 3-D data set and exporting a 2-D data trace. Fig. 4 is a schematic of such an interferometer. However, any non-contact optical interferometer that has pixel-to-pixel spacings as specified in Table 1 and that is capable of performing the test procedure with a vertical resolution less than 1 nm is permitted. The interferometer must be capable of measuring step heights to at least 5 µm higher than the step height to be measured

NOTE 1—Table 1 does not include magnifications at or less than 2.5× because the pixel-to-pixel spacings will be too large for this work or the possible introduction of a second set of interferometric fringes in the data set at these magnifications can adversely affect the data, or both. Therefore, magnifications at or less than 2.5× shall not be used.

7.2 A10-*µm-grid (or finer grid) Ruler*, for calibrating the interferometer in the *xy*-plane. This ruler should be longer than the maximum field of view at the lowest magnification.

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[3] The boldface numbers in parentheses refer to the list of references at the end of this standard.

[4] The same apparatus is used as in Test Method E2244 and Test Method E2246.

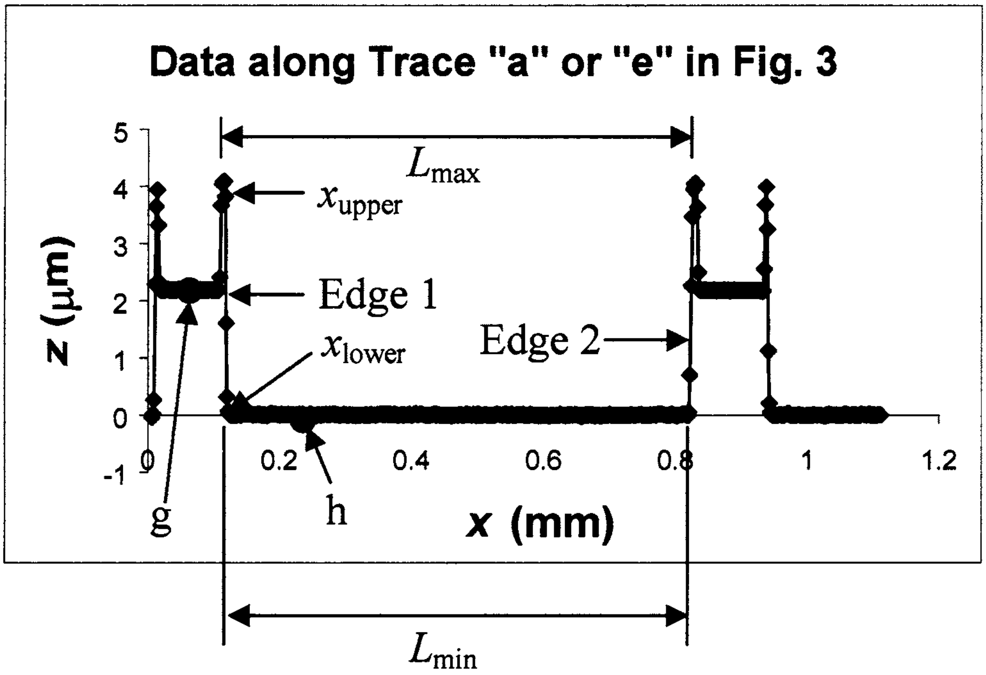

FIG. 5 2-D Data Trace Used to Find $x1_{min}$, $x1_{max}$, $x2_{min}$, and $x2_{max}$

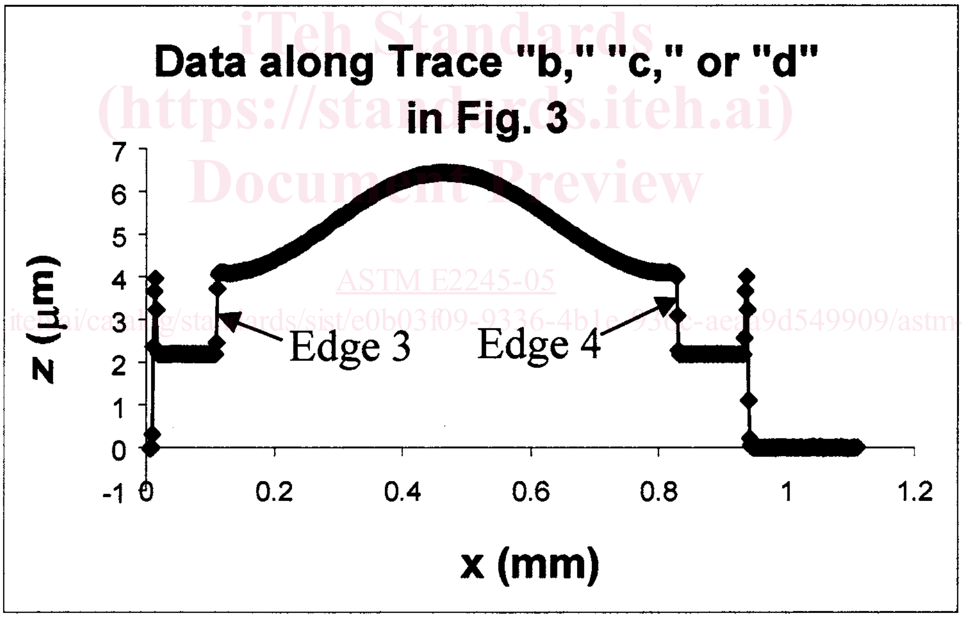

FIG. 6 2-D Data Trace Along a Fixed-Fixed Beam

TABLE 1 Interferometer Pixel-to-Pixel Spacing Requirements

Magnification, ×	Pixel-to-pixel spacing, µm
5	< 1.57
10	< 0.83
20	< 0.39
40	< 0.21
80	< 0.11

7.3 *Double-sided Step Height Standard*, for calibrating the interferometer in the out-of-plane *z*-direction.

8. Test Units

8.1 *Fixed-fixed Beam Test Structures Fabricated in Either a Surface-micromachining or Bulk-micromachining Process*—The design of a representative surface-micromachined fixed-fixed beam is specified below.

8.1.1 The fixed-fixed beam shall be wide enough (for example, 5-µm wide, as shown in Fig. 2) such that obtaining a 2-D data trace (such as Trace "c" in Fig. 3) along its length is not a difficult task.

8.1.2 The fixed-fixed beam shall be long enough (for example, $L \geq 400$ µm, as shown in Fig. 2) such that it exhibits out-of-plane curvature in the *z*-direction (as shown in Fig. 1 and Fig. 6). The approximate location of the two inflection points, created by this curvature, should be relatively easy to determine from a 2-D data trace (such as Trace "b," "c," or "d" in Fig. 3, as shown in Fig. 6) taken along the length of the beam.

8.1.3 The anchor lip between Edges "1" and "3" in Fig. 3 and between Edges "2" and "4" shall be wide enough to include at least three data points. If the pixel-to-pixel spacing is 1.56 µm, then these anchor lips should be at least 3.2 times greater (or 5.0 µm, as shown in Fig. 2). At the same time, they should be less than or equal to 10.0-µm wide.

8.1.4 The cut in the sacrificial layer that defines the anchor should be at least 50 by 50 µm (as shown in Fig. 2) to determine if the fixed-fixed beam has adhered to the top of the underlying layer as ascertained in Appendix X2.

NOTE 2—If one or more "posts" are used in the anchor area, a post layer is not considered the underlying layer. The post or posts connect the underlying layer to the sample material, in which case replace the words "cut in the sacrificial layer" with the words "post or posts."

8.1.5 Each anchor shall extend beyond the width of the fixed-fixed beam in the ±*y*-directions (for example, at least 5.0 µm, as shown in Fig. 2) such that obtaining Traces "a" and "e" in Fig. 3 is not a difficult task.

8.1.6 There should be only one fixed-fixed beam for each anchor (as shown in Fig. 2).

8.1.7 The underlying layer shall be unpatterned beneath the structural layer of interest and should extend at least 5.0 µm beyond the outermost edges of this patterned, structural layer (as shown in Fig. 2). However, the underlying layer should extend at least 50 µm beyond the anchor lip in the minus *x*-direction (as shown in this figure) to ascertain if the fixed-fixed beam has adhered to the top of the underlying layer, if necessary.

NOTE 3—Any tilt in the sample (or the sample data) is eliminated by leveling the interferometric optics (or the 3-D data set) with respect to the top of the exposed underlying layer. The exposed underlying layer straddling the fixed-fixed beam in Fig. 2 is used for this purpose. Therefore, no other structures should be designed in these areas.

8.1.8 A sufficient number of fixed-fixed beams (preferably of different lengths) should be fabricated in order to obtain at least one fixed-fixed beam after fabrication, which exhibits out-of-plane curvature in the *z*-direction and which has not adhered to the top of the underlying layer.

9. Calibration [5] (1)

9.1 Calibrate the interferometer in the *x*- and *y*-directions using a 10-µm-grid (or finer grid) ruler. Do this for each combination of lenses used for the measurements. Calibrate in the *xy*-plane on a yearly basis.

9.1.1 *For Non-reflective Rulers*:

9.1.1.1 Orient the ruler in the *x*-direction using crosshairs, if available. Record $ruler_x$ as measured on the interferometer's screen. Determine σ_{xcal}.

9.1.1.2 Orient the ruler in the *y*-direction using crosshairs, if available. Record $ruler_y$ as measured on the interferometer's screen. Determine σ_{ycal}.

9.1.1.3 Determine the *x*- and *y*-calibration factors using the following equations:

$$cal_x = ruler_x / inter_x \tag{1}$$

and

$$cal_y = ruler_y / inter_y \tag{2}$$

NOTE 4—Multiply the *x*- and *y*-data values obtained during the data session by the appropriate calibration factor to obtain calibrated *x*- and *y*-data values.

9.1.2 *For Reflective Rulers*:

9.1.2.1 Orient the ruler in the *x*-direction along the bottom edge of the field of view using crosshairs (if available).

9.1.2.2 Select the detector array size that achieves the best lateral resolution.

9.1.2.3 Adjust the intensity with respect to the brightest layer of interest.

9.1.2.4 Eliminate any tilt in the sample by nulling the fringes on the top of the flattest region of the ruler.

9.1.2.5 Recheck the sample alignment.

9.1.2.6 Take an average of at least three measurements to comprise one 3-D data set. Level the 3-D data set, with respect to flat regions of the ruler that are chosen to be symmetrically located with respect to the ruler, if possible.

9.1.2.7 Move the ruler slightly in the *y*-direction and obtain another leveled 3-D data set.

9.1.2.8 Continue until the ruler is out of the field of view.

NOTE 5—Obtain at least five data sets representative of the field of view.

9.1.2.9 For each leveled 3-D data set, extract a 2-D data trace in the *xz*-plane at the same location on the ruler, if possible.

9.1.2.10 Record in tabular form the ruler measurements versus *x* for each *y*.

9.1.2.11 Orient the ruler in the *y*-direction along the left-hand edge of the field of view. Repeat the above steps in a similar manner.

NOTE 6—This step can be skipped if the in-plane measurements are restricted to the *x*-direction due to a smaller pixel-to-pixel spacing in that direction.

9.1.2.12 By interpolating or extrapolating, or both, use the newly created calibrated lookup table(s) to find the calibrated *x* (or *y*, or both) values for pertinent pixels within the field of view. In the vicinity of the measurements to be taken, determine cal_x (or cal_y, or both), as given in Eq 1 (or Eq 2, or both). Also determine σ_{xcal} (or σ_{ycal}, or both).

9.2 Calibrate the interferometer in the out-of-plane *z*-direction using the certified value of a double-sided step height standard. Do this for each combination of lenses used for the measurements.

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[5] The same calibration procedure is used as in Test Method E2244 and Test Method E2246.

NOTE 7—Calibrating the step height at NIST[6] lowers the total uncertainty in the certified value.

9.2.1 Before the data session, record the height of the step height standard at six locations, three spread out evenly along each side of the step height standard. Use six, 3-D data sets to accomplish this task.

9.2.2 After the data session, record the height of the step height standard at six locations, three spread out evenly along each side of the step height standard. Use six, 3-D data sets to accomplish this task.

9.2.3 Calculate the mean value of the twelve measurements and the standard deviation (σ_{zcal}).

9.2.4 Determine the *z*-calibration factor using the following equation:

$$cal_z = cert / mean \tag{3}$$

NOTE 8—Multiply the *z*-data values obtained during the data session by cal_z to obtain calibrated *z*-data values.

10. Procedure (1)

10.1 For a surface-micromachined fixed-fixed beam, to obtain three data points that define each cosine function, five steps are taken: (*1*) select four transitional edges, (*2*) obtain a 3-D data set, (*3*) ensure alignment, (*4*) determine the endpoints of the in-plane length measurement, and (*5*) obtain three data points that define each cosine function.

NOTE 9—See Appendix X1 for the modifications to this procedure for a bulk-micromachined fixed-fixed beam. Also, situations may arise (for example, when the transitional edges are greater than 8 µm in height) where a surface-micromachined fixed-fixed beam should be treated as a bulk-micromachined fixed-fixed beam using the procedure in Appendix X1.

10.2 *Select Four Transitional Edges*:

10.2.1 Select two transitional edges that define the in-plane length measurement (for example, Edges "1" and "2" in Fig. 3).

NOTE 10—These are the first and second transitional edges. The first transitional edge has *x* (or *y*) values that are less than the *x* (or *y*) values associated with the second transitional edge.

10.2.2 Select two transitional edges to ensure alignment (for example, Edges "1" and "2" in Fig. 3). These transitional edges should be aligned parallel or perpendicular to the *x*- (or *y*-) axis of the interferometer.

10.3 *Obtain a 3-D Data Set*:

10.3.1 Orient the in-plane length, *L*, of the fixed-fixed beam in the interferometer's *x*-direction, if possible, if the interferometer's pixel-to-pixel spacing is smaller in the *x*-direction than in the *y*-direction. Otherwise, an orientation in the *y*-direction is acceptable.

10.3.2 Obtain a 3-D data set that contains 2-D data traces (*a*) parallel to the in-plane length of the fixed-fixed beam and (*b*) perpendicular to the transitional edges in 10.2.

10.3.2.1 Use the most powerful objective possible (while choosing the appropriate field of view lens, if applicable) given the sample areas to be investigated.

10.3.2.2 Select the detector array size that achieves the best lateral resolution.

10.3.2.3 Visually align the transitional edges in the field of view using crosshairs (if available).

10.3.2.4 Adjust the intensity with respect to the brightest layer of interest.

10.3.2.5 Eliminate any tilt in the sample by nulling the fringes on the top of the exposed underlying layer that straddles the fixed-fixed beam.

10.3.2.6 Recheck the sample alignment.

10.3.2.7 Take an average of at least three measurements to comprise one 3-D data set. Level the 3-D data set with respect to the top of the underlying layer with regions chosen to be symmetrically located with respect to the fixed-fixed beam. The *z* values of the data points along the top of the underlying layer are expected to lie between ±40 nm.

10.3.2.8 From the leveled 3-D data set, extract Trace "c" in Fig. 3.

10.3.2.9 In Trace "c," examine the data associated with the suspended portion of the fixed-fixed beam. If the fixed-fixed beam bends towards the underlying layer and there is a question as to whether or not it has adhered to the top of the underlying layer, calibrate the data trace in the *x*- (or *y*-) and *z*-directions and follow the steps in Appendix X2 at this point.

10.4 *Ensure Alignment*:

10.4.1 From the leveled 3-D data set in 10.3.2.7, choose Traces "a" and "e" (in Fig. 3, as shown in Fig. 5).

10.4.2 Calibrate Traces "a" and "e" in the *x*- (or *y*-) and *z*-directions.

10.4.3 Obtain x_{upper} and x_{lower} for Edges "1" and "2" in Traces "a" and "e" using the procedures given in 10.4.4 and 10.4.5. Therefore, eight values are obtained.

10.4.4 *Procedure to Find* x_{upper}:

10.4.4.1 Locate two points ("g" and "h") on either side of the transitional edge being examined (such as, Edge "1" in Fig. 5). Choose Point "g" to be located beyond the upper part of the transitional edge. Choose Point "h" to be located beyond the lower part of the transitional edge.

NOTE 11—Point "g" has a *z*-data value that is higher than the *z*-data value for Point "h."

10.4.4.2 Examine the out-of-plane *z*-data values one-by-one going from Point "h" to Point "g" in Fig. 5.

10.4.4.3 Along the upper half of the transition, the *x* value associated with the first *z* value, which is less than 300 nm from the next *z* value, is called x_{upper}.

NOTE 12—The difference in the *z* value of two neighboring points along the transitional edge is large (that is, typically greater than 500 nm). Along the anchor lip, this difference is a lot less (that is, typically less than 100 nm). The 300 nm criteria allows for an anchor lip that is not flat, rougher surfaces, and other phenomena. The 300 nm criteria may need to be modified, for example, when higher magnification lenses are used or for peculiarities in the sample or the 2-D data trace being examined, or both.

10.4.5 *Procedure to Find* x_{lower}:

10.4.5.1 Examine the *z*-data values one-by-one. However, this time go from Point "g" to Point "h" in Fig. 5.

10.4.5.2 Skip over the data points until a *z* value is obtained that is less than 75 nm.

NOTE 13—The *z* values of the data points along the top of the

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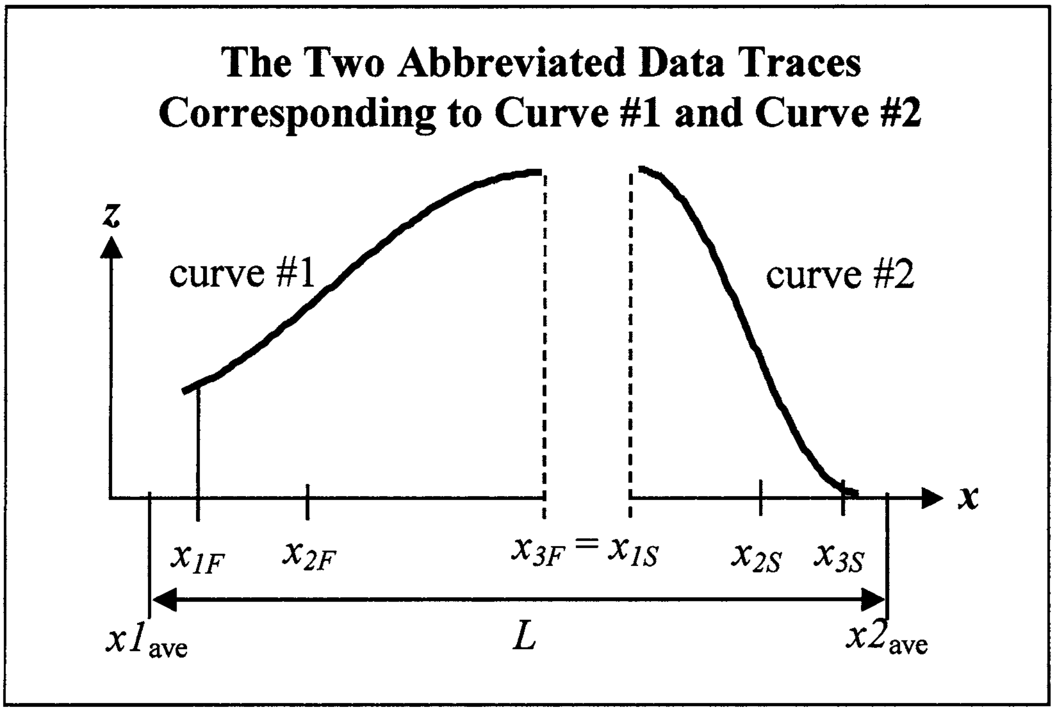
[6] The step heights are calibrated at NIST using a stylus instrument as specified in (**2**) and Appendix A of (**3**).



NOTE—The data above has been exaggerated.

FIG. 7 First and Second Curves Used to Find Residual Strain

underlying layer are expected to lie between ±40 nm. Choosing the first z value that is less than 75 nm allows for poor leveling, rougher surfaces, and other phenomena. The 75 nm criteria may need to be modified for peculiarities in the sample or the 2-D data trace being examined, or both.

10.4.5.3 The x value associated with the newly found z value is x_{lower}.

10.4.6 Compare the two values for $x1_{upper}$ in Traces "a" and "e."

10.4.7 Compare the two values for $x1_{lower}$ in Traces "a" and "e."

10.4.8 Compare the two values for $x2_{upper}$ in Traces "a" and "e."

10.4.9 Compare the two values for $x2_{lower}$ in Traces "a" and "e."

10.4.10 If more than half of the comparisons performed in 10.4.6-10.4.9, inclusive, result in compared values that are not identical, rotate the sample slightly, obtain another 3-D data set as detailed in 10.3, and repeat the steps in 10.4.

NOTE 14—The compared values correspond to discrete pixel locations. Therefore, obtaining identical x values between two traces is not an insurmountable task. However, if alignment cannot be achieved as specified above (for example, when higher magnification lenses are used), visually align the sample within the field of view of the interferometer.

10.5 *Determine the Endpoints of the In-plane Length Measurement*:

10.5.1 Choose the 2-D data trace within the 3-D data set to determine L (such as Trace "a" or "e" in Fig. 3). This trace passes through and is perpendicular to the two selected transitional edges in 10.2.1.

10.5.2 Calibrate the 2-D data trace in the x- (or y-) and z-directions, if not already done.

10.5.3 Obtain $x1_{max}$ and $x1_{min}$ using the procedures in 10.4.4 and 10.4.5, respectively, for Edge "1."

10.5.4 Obtain $x2_{max}$ and $x2_{min}$ using the procedures in 10.4.4 and 10.4.5, respectively, for Edge "2."

10.5.5 Calculate the endpoints (that is, $x1_{ave}$ and $x2_{ave}$) of the in-plane length measurement using the following equations:

$$x1_{ave} = (x1_{min} + x1_{max}) / 2 \quad (4)$$

$$x2_{ave} = (x2_{min} + x2_{max}) / 2 \quad (5)$$

10.6 *Obtain Three Data Points That Define Each Cosine Function*:

10.6.1 Choose a centrally located 2-D data trace (within the 3-D data set) along the fixed-fixed beam (such as Trace "c" in Fig. 3, as shown in Fig. 6).

10.6.2 Calibrate the 2-D data trace in the x- (or y-) and z-directions, if not already done.

10.6.3 Eliminate the data values at both ends of the trace that will not be included in the modeling (such as all data values outside and including Edges "3" and "4" in Fig. 6 with the x values of all the remaining data points lying between $x1_{ave}$ and $x2_{ave}$, inclusive).

10.6.4 Divide the remaining data into two abbreviated data traces (as shown in Fig. 7). The division should occur at the x (or y) value corresponding to the maximum (or minimum) z value. Include this data point in both data traces.

10.6.5 Choose three data points (with the subscript "F") from the first abbreviated data trace, that is:

10.6.5.1 An initial data point (x_{1F}, z_{1F}) such that $x1_{ave} \leq x_{1F}$,

10.6.5.2 The last data point (x_{3F}, z_{3F}), and

10.6.5.3 A centrally located data point (x_{2F}, z_{2F}) such that $x_{1F} < x_{2F} < x_{3F}$ and such that it is located at or near the inflection point.

10.6.6 Choose three data points (with the subscript "*S*") from the second abbreviated data trace, that is:

10.6.6.1 The first data point (x_{1S}, z_{1S}), where $x_{3F} = x_{1S}$,

10.6.6.2 A final data point (x_{3S}, z_{3S}) such that $x_{3S} \le x2_{ave}$, and

10.6.6.3 A centrally located data point (x_{2S}, z_{2S}) such that $x_{1S} < x_{2S} < x_{3S}$ and such that it is located at or near the inflection point.

11. Calculation (1)

11.1 Given $x1_{ave}$ and $x2_{ave}$ from 10.5.5 and the three data points for each abbreviated data trace from 10.6.5 and 10.6.6, four steps are used to calculate the residual strain:[7] (*1*) solve three equations for three unknowns (for each abbreviated data trace) to obtain each cosine function, (*2*) plot the functions with the data, (*3*) calculate the length of the curved fixed-fixed beam, and (*4*) calculate the residual strain.

11.2 *For the First Curve, Solve Three Equations for Three Unknowns:*:

11.2.1 The three equations are:

$$w = \pi + (\pi - w_{1F})(x - x_{3F}) / (x_{3F} - x_{1F}) \tag{6}$$

$$z_{1F} = s\,A_F \cos(w_{1F}) + z_{3F} + s\,A_F \tag{7}$$

$$z_{2F} = s\,A_F \cos(w_{2F}) + z_{3F} + s\,A_F \tag{8}$$

or

$$w_{2F} = \pi + (\pi - w_{1F})(x_{2F} - x_{3F}) / (x_{3F} - x_{1F}) \tag{9}$$

$$A_F = s\,(z_{1F} - z_{3F}) / (\cos(w_{1F}) + 1) \tag{10}$$

$$z_{2F} = [(z_{1F} - z_{3F})\cos(w_{2F}) + z_{3F}\cos(w_{1F}) + z_{1F}] / (\cos(w_{1F}) + 1) \tag{11}$$

NOTE 15—Eq 6 is an *x*-to-*w* transformation equation where the *w*-axis has π units.

11.2.2 Find the three unknowns (w_{1F}, w_{2F}, and A_F):

11.2.2.1 Assume $w_{1F} = 0$ and $w_{1F\Delta} = \pi/2$ where $w_{1F\Delta}$ is an assigned increment which gets smaller with each iteration, as shown in 11.2.2.6.

11.2.2.2 Solve Eq 9 to find w_{2F}.

11.2.2.3 Solve Eq 11 to find z_{2F}.

11.2.2.4 If the data value for z_{2F} (or z_{2Fdata}) is greater than the calculated value for z_{2F} (or z_{2Fcalc}), let $w_{1F} = w_{1F} + w_{1F\Delta}$ for upward bending fixed-fixed beams (that is, when $s = -1$).

NOTE 16—For downward bending fixed-fixed beams, let $w_{1F} = w_{1F} - w_{1F\Delta}$.

11.2.2.5 If z_{2Fdata} is less than z_{2Fcalc}, let $w_{1F} = w_{1F} - w_{1F\Delta}$ for upward bending fixed-fixed beams.

NOTE 17—For downward bending fixed-fixed beams, let $w_{1F} = w_{1F} + w_{1F\Delta}$.

11.2.2.6 Let $w_{1F\Delta} = w_{1F\Delta}/2$.

11.2.2.7 Repeat steps 11.2.2.2-11.2.2.6 until $z_{2Fcalc} = z_{2Fdata}$ to the preferred number of significant digits.

NOTE 18—Repeating these steps 1000 times in a computer program undoubtedly accomplishes this task.

11.2.2.8 Solve Eq 10 for A_F.

11.3 *For the Second Curve, Solve Three Equations for Three Unknowns*:

11.3.1 The three equations are:

$$w = w_{3S} + (w_{3S} - \pi)(x - x_{3S}) / (x_{3S} - x_{1S}) \tag{12}$$

$$z_{2S} = s\,A_S \cos(w_{2S}) + z_{1S} + s\,A_S \tag{13}$$

$$z_{3S} = s\,A_S \cos(w_{3S}) + z_{1S} + s\,A_S \tag{14}$$

or

$$w_{2S} = w_{3S} + (w_{3S} - \pi)(x_{2S} - x_{3S}) / (x_{3S} - x_{1S}) \tag{15}$$

$$A_S = s\,(z_{3S} - z_{1S}) / (\cos(w_{3S}) + 1) \tag{16}$$

$$z_{2S} = [(z_{3S} - z_{1S})\cos(w_{2S}) + z_{1S}\cos(w_{3S}) + z_{3S}] / (\cos(w_{3S}) + 1) \tag{17}$$

NOTE 19—Eq 12 is an *x*-to-*w* transformation equation where the *w*-axis has π units.

11.3.2 Find the three unknowns (w_{2S}, w_{3S}, and A_S):

11.3.2.1 Assume $w_{3S} = 2\pi$ and $w_{3S\Delta} = \pi/2$ where $w_{3S\Delta}$ is an assigned increment which gets smaller with each iteration, as shown in 11.3.2.6.

11.3.2.2 Solve Eq 15 to find w_{2S}.

11.3.2.3 Solve Eq 17 to find z_{2S}.

11.3.2.4 If the data value for z_{2S} (or z_{2Sdata}) is greater than the calculated value for z_{2S} (or z_{2Scalc}), let $w_{3S} = w_{3S} - w_{3S\Delta}$ for upward bending fixed-fixed beams (that is, when $s = -1$).

NOTE 20—For downward bending fixed-fixed beams, let $w_{3S} = w_{3S} + w_{3S\Delta}$.

11.3.2.5 If z_{2Sdata} is less than z_{2Scalc}, let $w_{3S} = w_{3S} + w_{3S\Delta}$ for upward bending fixed-fixed beams.

NOTE 21—For downward bending fixed-fixed beams, let $w_{3S} = w_{3S} - w_{3S\Delta}$.

11.3.2.6 Let $w_{3S\Delta} = w_{3S\Delta}/2$.

11.3.2.7 Repeat steps 11.3.2.2-11.3.2.6 until $z_{2Scalc} = z_{2Sdata}$ to the preferred number of significant digits.

NOTE 22—Repeating these steps 1000 times in a computer program undoubtedly accomplishes this task.

11.3.2.8 Solve Eq 16 for A_S.

11.4 *Plot the Functions with the Data*:

11.4.1 Plot the two abbreviated data traces from 10.6.4 along with the following equations:

$$z = s\,A_F \cos[\pi + (\pi - w_{1F})(x - x_{3F}) / (x_{3F} - x_{1F})] + z_{3F} + s\,A_F \tag{18}$$

where
$x1_{ave} \le x \le x_{3F}$
and

$$z = s\,A_S \cos[w_{3S} + (w_{3S} - \pi)(x - x_{3S}) / (x_{3S} - x_{1S})] + z_{1S} + s\,A_S \tag{19}$$

where
$x_{1S} \le x \le x2_{ave}$

11.4.2 For each abbreviated data trace, if one of the three chosen data points in 10.6.5 or 10.6.6 is not representative of the data, alter its *z* value and repeat the analysis beginning at 11.1.

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[7] By inserting the inputs into the correct locations on the appropriate NIST Web page (*http://www.eeel.nist.gov/812/test-structures/MEMSCalculator.htm*), steps 1, 3, and 4 can be performed on-line in a matter of seconds.