Designation: D6991 – 05 (Reapproved 2010)

Standard Test Method for Measurements of Internal Stresses in Organic Coatings by Cantilever (Beam) Method[1]

This standard is issued under the fixed designation D6991; 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 the procedure for measurements of internal stresses in organic coatings by using the cantilever (beam) method.

1.2 This method is appropriate for the coatings for which the modulus of elasticity of substrate (Es) is significantly greater than the modulus of elasticity of coating (Ec) and for which the thickness of substrate is significantly greater than thickness of coating (see Note 4 and Note 5).

1.3 The stress values are limited by the adhesion values of coating to the substrate and by the tensile strength of the coating, or both.

1.4 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.5 *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 to determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D823 Practices for Producing Films of Uniform Thickness of Paint, Varnish, and Related Products on Test Panels

D1186 Test Methods for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to a Ferrous Base (Withdrawn 2006)[3]

D1400 Test Method for Nondestructive Measurement of Dry Film Thickness of Nonconductive Coatings Applied to a Nonferrous Metal Base (Withdrawn 2006)[3]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *cantilever, n*—a beam or member securely fixed at one end and hanging free at the other end.

3.1.2 *deflection, n*—the displacement of a beam from its original position by an applied force.

3.1.2.1 *Discussion*—The deflection of the beam is used to measure that force acting on the tip.

3.1.3 *internal stress, n*—a stress system within a solid that is not dependent on external forces.

4. Test Method

4.1 Internal stresses in coatings are determined by the cantilever method (Fig. 1). Substrate A in the shape of a rectangular cantilever beam is clamped by its end B in a special fixture E. Coating (F) is applied to one side of the beam. Internal stresses occur in the film when it is being cured (drying, cross-linking, etc.). When there is sufficient adhesion between the coating and the substrate, the stresses bend the cantilever beam, forcing its free end D to be deflected from its original position by a distance of h. The deflection of the beam is measured under an optical microscope and internal stress is calculated using the equation for the cantilever method. See Eq 1 in Section 9, (Formula 1).

5. Significance and Use

5.1 Stresses in coatings arise as a result of their shrinkage or expansion if expected movements are prevented by coating adhesion to its substrate.

5.2 There are several causes leading to arrival of stresses in the coatings: film formation (cross-linking, solvent evaporation, etc.); differences in thermal expansion coefficients between coating and substrate; humidity and water absorption; environmental effects (ultraviolet radiation, temperature and humidity), and others.

5.3 Knowledge of the internal stresses in coatings is very important because they may effect coating performance and service life. If the internal stress exceeds the tensile strength of the film, cracks are formed. If stress exceeds adhesion between

[1] This test method is under the jurisdiction of ASTM Committee D01 on Paint and Related Coatings, Materials, and Applications and is the direct responsibility of Subcommittee D01.23 on Physical Properties of Applied Paint Films.

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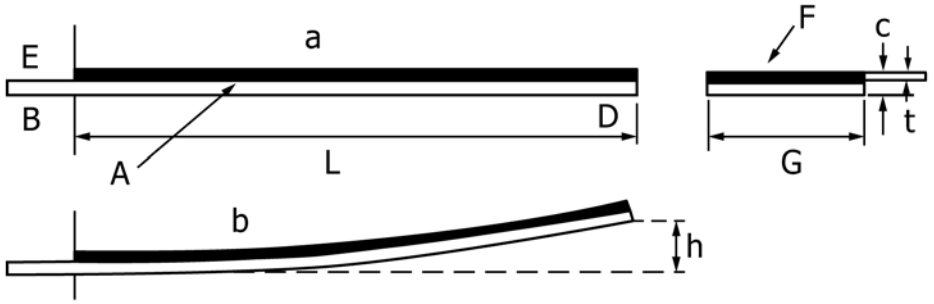
[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.



A- Cantilever beam (substrate)
B- Beam end clamped in Fixture E
c- Coating thickness
D- Free end deflected under stress
E- Fixture
F- Coating
G- Width of beam
h- Deflection
L- Distance between the deflecting point and the clamping point.
t- Substrate thickness

FIG. 1 Diagram of the Cantilever Method for Measurements of Internal Stresses in Organic Coatings
a – Original position b – Free end deflected from its original position as a result of stress

coating and substrate, it will reduce adhesion and can lead to delamination of coatings. Quantitative information about stresses in coatings can be useful in coating formulation and recommendations for their application and use.

5.4 This method has been found useful for air-dry industrial organic coatings but the applicability has not yet been assessed for thin coatings (thickness <0.0254 mm (.001 in.), for powder and thermally-cured coatings.

6. Apparatus

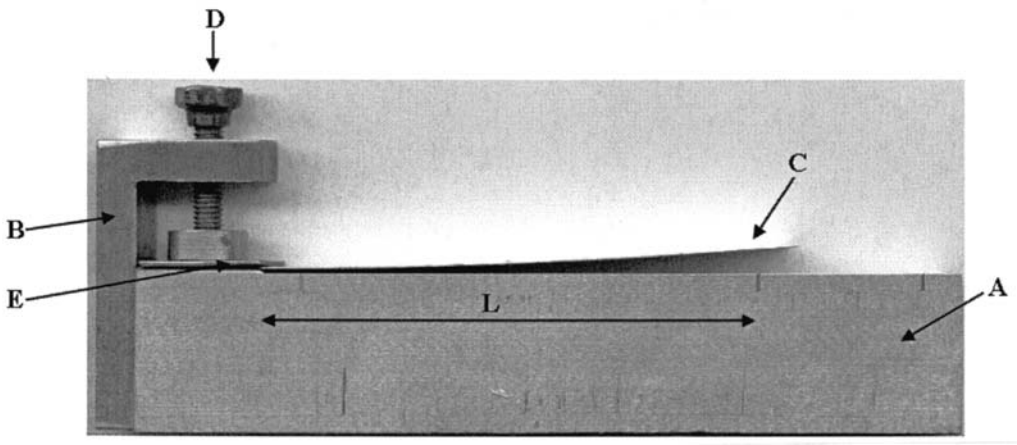
6.1 *Measurement Fixture (*Fig. 2*)*—The fixture consists of the support A and the stop B to which the cantilever substrate C is clamped with the screw D and shim E. On the side of the support there is an engraved mark called the fixed point at an exact known distance (L) from the edge clamping point. By moving the fixture under an optical microscope, the deflection of the cantilever is always measured at the fixed point.

6.2 *Optical Microscope*—Capable of measuring deflection with resolution 0.0254 mm (0.001 in.).

7. Test Specimen

7.1 Use stainless strips (stainless steel 304SS is acceptable) as a cantilever substrate with the following dimensions: width, 12 mm (0.5 in.); length, 102 mm (4 in.); and thickness, 0.254 mm (0.01 in.).

NOTE 1—Other dimensions could be used. However, to reduce effect of clamping, the length of cantilever strip between the edge point at which it is clamped and the point at which deflection is measured (see Fig. 1)



A- Support
B- Stop
C- Coated cantilever beam
D- Screw clamp
E- Pressure shim
L- Distance between end of pressure shim to the engraved point where the deflection is measured

FIG. 2 Fixture with the Clamped Coated Cantilever Sample for the Measurements of Internal Stresses in Organic Coatings

should be greater than 80 mm.[4,5]

Stainless steel was selected to avoid corrosion of the strips. However, in cases where the coating can not adhere to the stainless steel, the other materials can be used (carbon steel, aluminum, etc.).

7.2 Cantilever substrates are selected with a slight cylindrical curvature with a "concave" side to be coated. If the strips are flat the "slight curvature" can be made by gently bending them with hand to achieve 2-3 mm deflection.

7.3 Install the cantilever in the fixture and measure using microscope the deflection at fixed point before coating application.

7.4 Substrate should be degreased or solvent-cleaned; in some cases, surface can be slightly and uniformly abraded using abrasive paper.

7.5 The clamped area and the uncoated side of the cantilever substrate are masked with tape during the application of coating.

7.6 Apply uniform coatings of the material to be tested to the "concave" side of the cantilever strip at specified thickness in accordance with Practices D823. The thickness should not be greater than half the thickness of the cantilever panel (see Note 4). For example, if substrate thickness is 0.254 mm (0.01 in.) the recommended coating thickness should be not greater than 0.127 mm (0.005 in.). Due to the slower process of curing in very thick coatings it is recommended to limit the coating thickness to 0.254 – 0.381 mm (0.01 – 0.015 in.).

7.7 Remove any paint from the uncoated side by sharp razor blade if necessary. Prepare a minimum of three coated panels for the material.

7.8 Cure the coated panels under humidity and temperature conditions as agreed upon between the producer and the user.

7.9 The thickness of the dry coatings should be measured in accordance with Test Methods D1186, Test Method D1400 or any other test method as agreed upon between the producer and the user.

7.10 Take any precautions in handling of the cantilever beam during preparation for application, masking, application, mask removal, etc., to avoid any deformation or damage.

8. Measurement Procedure

8.1 As soon as the coating is dry enough to be handled, the coated beam is clamped finger tight to the support with coated side up. The masking tape should be removed before installation.

8.2 The first deflection measurement taken under microscope should be made as soon as the coating is dry enough to handle, at which point there should be minimal or no measurable deflection. This measurement is used as a "zero" reference point.

NOTE 2—If coating rapidly cures and develops stress, the reference position of the cantilever substrate cannot be correctly determined. For such cases the deflection obtained with the uncoated substrate is taken as the "zero" point.

8.3 The difference between current values taken at the specified time intervals and "zero" values is the deflection to be used in stress calculations.

8.4 The stress (deflection) can be measured as a function of time and of difference variables (temperature, humidity, coating thickness, etc.). Coated samples can be clamped in the fixture for the period of testing, or can be removed for various exposures and reinstalled again.

NOTE 3—Sample reinstallation may increase the error of measurement.

9. Calculation of Internal Stress

9.1 Internal Stress is calculated by using Eq 1 (Formula 1) developed by Corcoran[6]:

$$S = \frac{hE_s t^3}{3L^2 c(t+c)(1-\gamma_s)} \quad (1)$$

where:

S = internal stress, MPa (PSI),
h = deflection of the cantilever, mm (in.),
E_s = modulus of elasticity of substrate, for stainless steel 304SS, typically 19.3 by 10^4 MPa (28 by 10^6 PSI),
γ_s = Poisson's ratio of the cantilever substrate (for stainless steel: 0.25),
L = length of the substrate between the edge point at which it is clamped and point of which deflection is measured, mm (in.),
t = thickness of the cantilever substrate, mm (in.), and
c = thickness of the coating, mm (in.).

NOTE 4—The precise relationship between internal stresses and deflection is expressed by Corcoran in Eq 2 (Formula 2), which consists of two members:

$$S = \frac{hE_s t^3}{3L^2 c(t+c)(1-\gamma_s)} + \frac{hE_c (t+c)}{L^2 (1-\gamma_c)} \quad (2)$$

where:

E_c = modulus of elasticity for coating, MPa (PSI) and
γ_c = Poisson's ratio of the coating (both usually unknown).

9.1.1 The first term in formula (2) expresses the stresses, which remain in the coating after bending. The second term expresses the stresses removed as a result of the bending of the substrate (stress relief). The stress S represents the stresses, which would have existed in the coating, applied over rigid inflexible substrate (as actual components of structures). When $E_s \gg E_c$ and $t \gg c$, the second term in Eq 2 can be neglected; the error will be smaller than the experimental error. This avoids the necessity of knowing the values of E_c and γ_c. So, only the first member in the Eq 1 can be used in calculations if $Es \gg E_c$ and $t \gg c$. Now the calculation of stresses is reduced to the Eq 1, which is recommended in this standard.

NOTE 5—Usually $E_c >> E_s$; the ratio between t and c should be carefully selected. For example, if t=c, the contribution of the second term in formula (2) will be up to 20 % if t=2c, the contribution will be 5-6 %

[4] Perera, D. Y., Eynde, D. V., "Considerations on a Cantilever (Beam) Method for Measuring the Internal Stress in Organic Coatings," *Journal of Coatings Technology*, Vol. 53, No. 677, June 1981.

[5] Korobov, Y., Salem, L., "Stress Analysis as a Tool in Coatings Research," *Materials Performance*, Vol. 29, No. 4, April 1990.

[6] Corcoran, E. M., "Determining Stresses in Organic Coatings using Plate Beam Deflection," *Journal of Paint Technology*, Vol. 41, No. 538. November 1969.

10. Report

10.1 Report the following information:

10.1.1 Complete identification of the test specimen: coating description, coating thickness (minimum, maximum, average, and its distribution along the length and width of the substrate), application conditions.

10.1.2 Complete identification of the cantilever substrate (material, length, width, and thickness; modulus of elasticity and Poisson's Ratio; length between clamping point and deflection measured point).

10.1.3 Report ratio between thickness of film to substrate.

10.1.4 Report if the sample was fixed at all times during the test or if it was periodically removed and reinstalled.

10.1.5 Report the deflection values, their corresponding time intervals and exposure conditions (temperature, humidity, etc.).

10.1.6 Report the calculated stress.

11. Precision and Bias

11.1 Accuracy of this method depends upon the following variables: precision of measuring the deflection, the ratio of the thickness of the coating and the substrate, length of the working part of the substrate, uniformity of applied film, reinstallation of cantilever in the fixture, and environment.

11.2 *Precision*—The pooled repeatability standard deviation has been determined to be 0.7 MPa representing a pooled coefficient of variation of 13 % These values were obtained using 6 different formulations and 2 different film thicknesses. 10 readings of each sample were made by one operator in one laboratory. See Appendix X2 for the precision data.

11.2.1 The reproducibility of this method and bias statements are not available at this time. Round robin tests will be performed at a later date within 5 years after the method is approved.

12. Keywords

12.1 cantilever; deflection; internal stress; organic coatings

APPENDIXES

(Nonmandatory Information)

X1. RECOMMENDED DIMENSIONS OF TESTING APPARATUS (see Fig. 1 and Fig. 2):

Fig.1

A – rectangular cantilever beam (substrate): made of 304SS stainless steel; width 12 mm (0.5 in.); length, 102 mm (4 in.); thickness t = 0.254 mm (0.01 in.);

Beam is clamped by its end **B** in a special fixture **E**; free end **D** is deflected under stress from its original position by a distance of **h** (deflection).

Fig.2

A (support): 127 by 25.4 by 12.7mm (5 by 1 by ½ in.); make small supporting base area 19 by 12.7 mm (¾ by ½ in.) for sample installation under the pressure shim and the screw-clamp. This base area should be 1.6 mm (1⁄16 in.) higher than the rest of the support surface; Polish base surface.

B (stop): L – shape; 45 by 25.4 mm (1 ¾ by 1 in.); thickness 6.4 mm (¼ in.); Stop should be attached to the support by two screws;

D (screw-clamp): screw with attached 12.7 mm (½ in.) diameter clamp;

L – distance between engraved point and clamping point >= 80 mm (3 in.).

Notes:

1. Use rectangular pressure shim 19 by 12.7 by 1.6 mm (¾ by ½ by 1⁄16 in.) between clamp and sample;
2. Use stainless steel for all parts to avoid corrosion;
3. Polish support base and clamping surface area to make them parallel;
4. Polish both sides of the pressure shim;
5. Make clamping screw perpendicular to the clamping surface.

X2. PRECISION DATA

TABLE X2.1 Repeatability of Stress Measurements Within One Lab by One Operator

		Stress Readings, psi												
Panel ID	DFT, mils	1 st	2 nd	3 rd	4 th	5 th	6 th	7 th	8 th	9 th	10 th	average	stdv	coef. Var, %
5A	3.0	708	885	708	708	708	885	708	531	531	885	726	131	18
5B	2.8	1155	1155	1155	963	963	1155	963	963	963	963	1040	99	10
9A	3.5	1022	1314	1314	1022	1022	1022	876	876	876	876	1022	169	16
9B	3.5	584	584	584	584	584	438	584	438	438	438	526	75	14
17A	4.2	694	810	694	694	578	578	578	578	578	578	636	82	13
17B	3.2	490	490	653	490	490	490	490	490	490	490	506	52	10
20A	3.6	846	846	987	846	846	846	846	705	705	705	818	89	11
20B	3.0	885	708	531	708	708	531	708	708	708	708	690	100	15
24A	3.0	1062	1062	1062	1062	1062	1062	885	1062	1062	1062	1044	56	5
24B	2.8	963	963	963	963	770	963	770	578	963	770	867	136	16
26A	3.6	987	846	846	846	846	846	846	846	987	846	874	59	7
												Pooled	102 psi	13
													0.7 MPa	