Designation: D7027 – 13

Standard Test Method for Evaluation of Scratch Resistance of Polymeric Coatings and Plastics Using an Instrumented Scratch Machine[1]

This standard is issued under the fixed designation D7027; 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 describes a laboratory procedure using an instrumented scratch machine to produce and quantify surface damage under controlled conditions. This test method is able to characterize the scratch resistance of polymers by measuring many significant material parameters. The scratch-inducing and data acquisition process is automated to avoid user-influenced effects that may affect the results.

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

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]

D618 Practice for Conditioning Plastics for Testing

D638 Test Method for Tensile Properties of Plastics

D1894 Test Method for Static and Kinetic Coefficients of Friction of Plastic Film and Sheeting

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

G99 Test Method for Wear Testing with a Pin-on-Disk Apparatus

G171 Test Method for Scratch Hardness of Materials Using a Diamond Stylus

3. Terminology

3.1 *Definitions:*

3.1.1 *ASV Software, n—Automatic Scratch Visualization*, a computer program which automates the identification of the point of failure in a rising load scratch tests using contrast as the failure criteria. The software determines failure if a continuous change in contrast between the scratch groove and the undamaged material surface reaches +3 %, -3 %, or ±3 %. The continuity criterion is defined as a region of length equal to 2 diameters of the scratch stylus with 90 % or more of the region exceeding the contrast criterion. The lowest load point on the scratch from which there is a continuous contrasting region is considered the point of failure. This program is useful for visual analysis of the test and may be used for other applications, such as pass-fail criterion for scratch visibility. An example of the application of ASV is shown in Fig. 1.

3.1.2 *critical normal load, n*—the normal load at which failure (see 3.1.4) of the material within the scratch groove first occurs.

3.1.3 *normal load, n*—a load applied onto the scratch stylus that is imposed in a vertically downward direction, perpendicular to the surface of the specimen. The normal load is also referred to as the "Z-direction load."

3.1.4 *point of failure, n*—the point along a rising-load scratch path at which the damage to the surface is first considered to be unacceptable. The point of failure for a given study shall be defined in a quantifiable manner. For aesthetic studies the recommended criteria is a contrast of ±3 % between the scratch groove and the undamaged material surface. For different studies other criteria for failure may be used. For example, failure may occur when the scratch width or depth exceeds a predetermined value. Onset of micro-cracking, crazing, fish-scale formation, plowing can also be used as failure criteria. For a coated specimen the point of failure might be defined as the point at which the coating is penetrated, revealing the underlying substrate. An image of styrene acrylonitrile (SAN) subjected to Test Mode A (4.1.1) under a linearly increasing normal load range of 1-90 N is shown in Fig. 1 to illustrate several possible points of failure that can occur during the scratch process.

3.1.5 *scratch coefficient of friction, n*—the ratio of the tangential force (3.1.10) to the normal load (3.1.3). This coefficient is a measure of the resistance of a material to scratching motion. For tests conducted under constant load, two distinct quantities may be characterized, the static and kinetic coefficients. The static coefficient is related to the

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[1] This test method is under the jurisdiction of ASTM Committee D20 on Plastics and is the direct responsibility of Subcommittee D20.10 on Mechanical Properties.

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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.

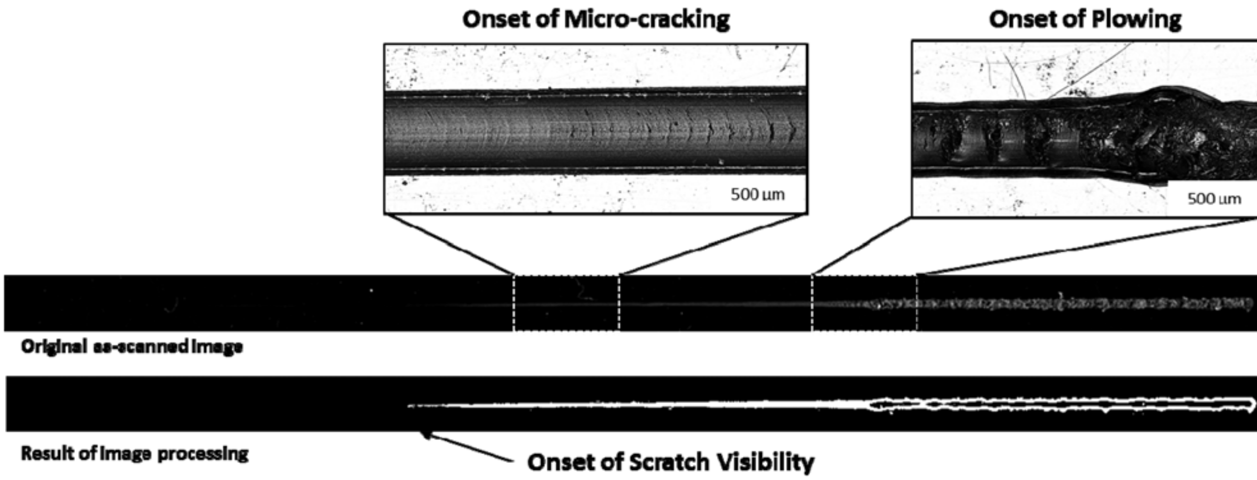

FIG. 1 Images of Polystyrene-Acrylonitrile (SAN) Subjected to Test Mode A Under a Progressive Load of 1-90 N Showing Examples of Points of Failure

tangential force measured prior to the movement of the scratch stylus while the kinetic coefficient is related to the constant tangential force measured in sustaining this movement. This quantity is not equivalent to the *coefficient of friction*, which is obtained in accordance with Test Method D1894 and is similar to the *stylus drag coefficient* as defined in Test Method G171.

3.1.6 *scratch depth, n*—the vertical distance to be measured from the trough of the scratch groove to the undisturbed specimen surface (D1) or to the peaks of the scratch path (D2). Refer to Fig. 2.

3.1.7 *scratch resistance, n*—ability to withstand damage that is accompanied by the gross deformation typically associated with sliding indentation of asperities that may involve compressing, plowing, and shearing of material. Quantification can be accomplished through the measurement of critical normal load scratch depth (3.1.6), scratch width (3.1.8) and other geometric or visual characteristics of the scratch.

3.1.8 *scratch width, n*—the horizontal distance between the two peaks on both sides of the scratch groove (W1). Refer to Fig. 2.

3.1.9 *scratching, v*—process involving surface deformation (displacement or mechanical removal, or both, of material) caused by the action of one of more asperities, or protuberances, or both, sliding across the surface.

3.1.10 *tangential force, n*—the force present at the interface between the scratch tip and the specimen, acting opposite to the direction of motion of the scratch tip. The tangential force acts parallel to the scratch direction and is composed of two components: the kinetic friction acting on the scratch tip, plus the reaction force generated during deformation of the surface. The magnitude of the component forces can vary. At small scratch depths the tangential force is kinetic friction. As scratch depth increases, the forces due to elastic and plastic deformation increase. Tangential force is also referred to as the "X-direction force" measured by the scratch instrument.

3.1.11 *whitening, n*—a phenomenon occurring as a result of light scattering by surface deformation resulting from the scratch process that causes the scratch path to be brighter, or "whiter," than the undisturbed background surface. Key deformation mechanisms include increase in surface roughness due to micro-cracking. Whitening is measurable as a contrast change between the scratch groove and the undamaged material surface.

4. Summary of Test Method

4.1 This test method utilizes an automated scratch machine to administer controlled scratch tests on polymeric specimens. Two basic test modes (Test Modes A and B) are presented.

4.1.1 *Test Mode A*—A scratch is applied onto the specimen surface under an increasing normal load from 2 to 50 N (±0.5 N) over a distance of 0.1 m (±0.0001 m) at a constant scratch rate of 0.1 m/s (±0.0005 m/s). This test mode is intended to determine the critical normal load for failure for a material system. The point of failure should occur in the second or third quartile of the test length. For materials that do not exhibit failure in this range, the load range may be changed to ensure that the point of failure occurs in the middle of the scratch path.

4.1.2 *Test Mode B*—A scratch is applied onto the specimen surface under a constant normal load of 30 N (±0.1 N) over a distance of 0.1 m (±0.0001 m) at a constant scratch rate of 0.1 m/s (±0.0005 m/s). This test mode is intended to evaluate the load-dependant homogeneous response of the material and establish the scratch coefficient of friction. The constant load value may be increased if 30 N is insufficient to generate damage on the specimen.

4.2 The scratched surface can be inspected visually or by using evaluation tools to study the surface damage. For Test Mode A, the critical normal load is determined by the point of failure criteria established for that experiment. Measurement of the scratch width, or depth, or both, may also be taken to aid the quantification of scratch resistance. ASV Software may be used to automate the measurement of the point of failure with regard to scratch visibility.

4.3 Scratch coefficient of friction as defined in 3.1.5 can be computed for material characterization using the tangential force and normal load data recorded during tests.

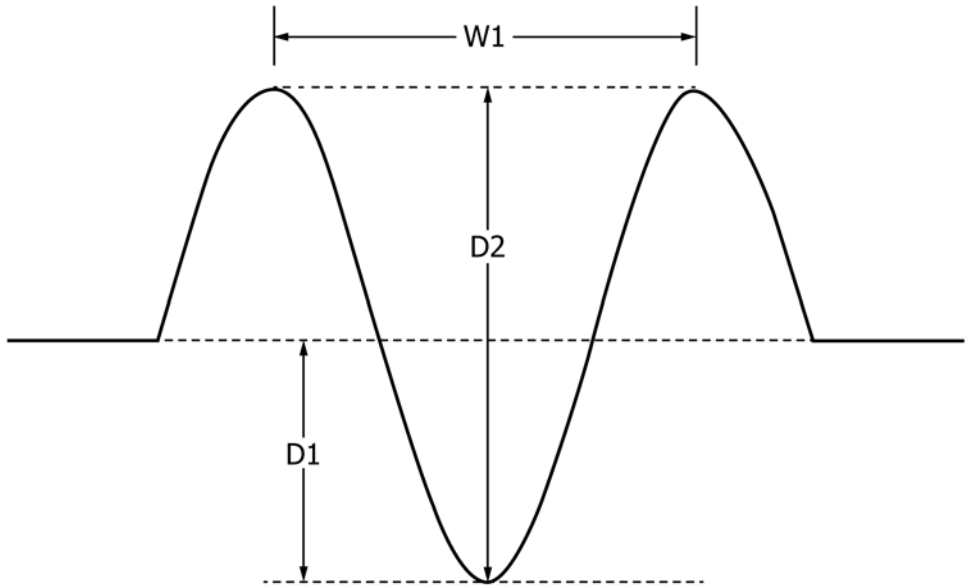

FIG. 2 Cross Section of Scratch Path Showing Scratch Width Measurement (W1) and Depth Measurements (D1 and D2)

5. Significance and Use

5.1 Scratch tests are performed on specimens:

(1) to evaluate the scratch resistance of a particular material,

(2) to rank the relative scratch resistance of different materials, or

(3) to determine the scratch coefficient of friction of materials.

5.2 Since polymers exhibit mechanical properties that are strongly dependent on temperature, the test standard prescribed herein is designed to yield reproducible results when users perform tests under the similar testing environment and on specimens of the same material and surface texture that are subjected to the same conditioning procedures.

5.3 Certain polymers are self-healing (recoverable) when subjected to scratches and other physical deformations because of their viscoelastic and relaxation properties. It is important to note the difference between the instantaneous (if readily measurable) and residual scratch damage and compare results appropriately to ensure reproducibility. It is recommended that 24 hours be allowed for viscoelastic recovery when considering residual scratch depth.

5.4 "Whitening" of the scratched surface is a key damage mechanism that has prompted much concern in automotive and other applications where surface aesthetics is important. This type of damage is undesirable because it is evident to the human eye. The critical normal load at which this phenomenon appears serves as a benchmark in ranking material performance, especially from an aesthetic point of view.

6. Apparatus

6.1 *General Description*—The instrumented scratch machine[3] described here has been developed at Texas A&M University under the auspices of the Scratch Behavior of Polymeric Materials Consortium. A schematic of the scratch machine is shown in Fig. 3. The instrument consists of a sample stage, clamping devices, a load generator, and a horizontal motion servo system. Optional systems such as a load and position sensing system, data acquisition and computer systems may be included when position and load data are required. An environmental chamber may also be added for sub-ambient and elevated temperature tests. Instruments like optical microscopes, flatbed scanners, image capturing tools, or an ASV (3.1.1) can be used for post-scratch evaluation.

6.2 *Spring-Load Mechanism*—The instrument is a stylus-type scratcher in which a 1-mm-diameter spherical tip is used to scratch the surface of a flat specimen. It consists of a sample stage with dimensions of 305 by 610 mm on which test specimens can be anchored. The spring-load driven mechanism, capable of generating 0 to 200 N of normal load, exerts the force onto the scratch stylus, either at a constant magnitude or increasing linearly to a desired magnitude.

6.3 *Horizontal Motion Servo System*—A high-precision motor, controlled via microprocessor, actuates the scratch

[3] The sole source of supply of the apparatus known to the committee at this time is Surface Machine Systems, LLC, http://www.surfacemachines.com. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee[1], which you may attend.

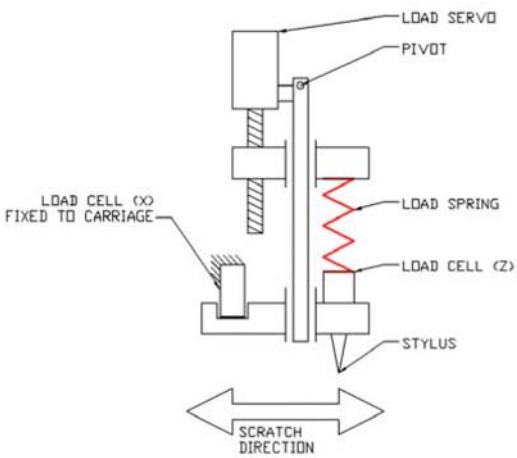

FIG. 3 Schematic of a Spring-Loaded Scratch Stylus Machine

stylus. The horizontal speed of the scratch stylus can be set at a constant rate between 0 and 400 mm/s.

6.4 *Load and Position Sensing System (optional)*—If required, the instrument may be equipped with devices to monitor the normal load, the tangential force, instantaneous scratch depth and horizontal position. The tangential force acting on the stylus shall be measured with an accuracy of ±0.1 N. The data acquired for depth, horizontal position and velocity of the stylus shall have an accuracy of ±0.5 µm, ±5 µm and ±0.0005 m/s, respectively.

6.5 *Data Acquisition and Computer Systems (optional)*—Connections from the sensing system to the computer system shall be insulated against electromagnetic interference to ensure clean and reliable data. The computer system shall have the capability to collect the force and position data. The data capture rate (samples per channel) shall be set to a minimum of 10 times the scratch velocity (mm/s) to guarantee reliable and accurate data. The data capture rate may be set higher if desired.

6.6 *Environmental Chamber (optional)*—An environmental chamber with heating and cooling controls allows experiments to be performed from –50 to 100°C.

6.7 *Evaluation Instruments*—Other than visual inspection, the scratch grooves can be further examined with optical microscopes, flatbed scanners, and/or profilometers for measuring scratch width and depth. These devices can also be used to determine the point of failure (such as the onset of micro-cracking, crazing, fish-scale formation, plowing, etc.). Since the capability and sensitivity of each device are different, it is required that the adopted method of evaluation be reported. For the purpose of quantifying whitening, other instruments that are capable of measuring reflected light intensity in the scratch groove can be used.

6.8 *Stylus Tip*—The setup of the scratch machine provides the added flexibility of allowing the interchangeability of stylus tips in their material and geometry. The suggested material for the scratch stylus tip is #440 Stainless Steel. Other materials for the stylus tip are acceptable so long as they have higher indentation hardness than the test material. The stylus tip shall be spherical in shape with a diameter of 1 mm (±2.54 µm); using a tip of other geometry is optional but their results shall not supersede those from the spherical tip tests.

7. Hazards

7.1 The scratch machine contains moving parts, and is capable of moving at high speed. Therefore, standard laboratory safety practices involving the use of machinery should be followed. Objects, samples and tools must not be stored on or near the scratch tester to avoid them being accidentally caught in the mechanism.

7.2 Eye protection must be worn at all times when conducting scratch tests.

7.3 The scratch machine operator shall take care that loose clothing, jewelry, long sleeves, and long hair are secured and kept away from the scratch machine.

7.4 Thermally insulated gloves must be worn when handling specimens at extreme temperatures. If testing is limited to room temperature only, thick gloves are not to be worn, though disposable latex gloves may be used to avoid skin-oil contamination on samples.

8. Test Specimens and Sample Preparation

8.1 *Materials*—The test method can be applied to a variety of bulk polymers, as well as coated materials. The materials must be able to be prepared to the desired dimensions and able to withstand the stresses imposed during the test without ultimate failure or excessive fracture. The materials being tested shall be described by dimensions, surface finish, material type, form, composition, processing treatment and, when appropriate, indentation hardness (see Test Method G99).

8.2 *Tensile Specimens*—Injection-molded tensile bars as specified in Test Method D638 (Test specimen I-IV) are acceptable for use with this test. Typical thickness shall be between 3 and 10 mm. Since the scratch length for different test modes is taken to be 100 mm, the specimen shall be at least 140 mm in length to provide enough area for clamping at both ends. Experiments have shown that thickness can affect scratch properties and care should be taken to ensure that the thicknesses of different specimens are consistent within the tolerance specified in Test Method D638.

8.3 *Plaque Specimens*—A plaque, at least 140 mm in length and 10 mm in width, shall be used. Thickness shall be at least 3 mm. Samples thinner than 3 mm may be tested with the use of a precision backing plate or spacer underneath the sample. It is possible to make multiple scratches on the same plaque so long as the grooves do not affect one another and the distance between the two neighboring grooves shall be no less than twice the stylus tip diameter. For injection-molded, polymeric materials, the scratch should be made along the melt flow direction for consistency.

8.4 *Sampling Size*—At least five specimens (or five runs) shall be tested to ensure repeatability.

8.5 *Surface Finish*—For material comparison, test specimens shall have the same surface texture and color, unless the experiment is performed to investigate the effect of surface texture and color. This is especially important for the detection of whitening in the scratch path as certain colors and grained textures tend to hide the surface damage better than others. Any imperfections in the sample including ejector-pin marks, sprues, gates, etc., must not be present on the underside of the sample in the area of the scratch path. If the specimen has pultrusions on the bottom side then these must be removed before testing.

9. Preparation of Apparatus

9.1 *Scratch Stylus Tip*—The scratch tip (stylus) shall be inspected frequently to ensure it is in good condition. Inspection shall be performed using a magnifying device capable of at least 10× magnification, such as a stereomicroscope, "pocket microscope" or loupe. If the tip shows mechanical damage such as chipping, visible abrasive wear, or breakage, the tip shall be immediately discarded and replaced. If foreign matter (such as debris from the scratch specimen) is found to be adhered to the tip then the tip shall be cleaned with an appropriate solvent and then re-inspected. Appropriate solvents for cleaning scratch tips include isopropyl alcohol, methanol, and acetone. HPLC grade solvents are recommended for tip cleaning. Solvents must be allowed to evaporate completely before the tip is returned to service. Scratch tips shall be cleaned with solvent anytime the scratch material system is changed. This is to prevent cross-contamination of slip agents, mold release agents, or other chemicals that may be present in some samples. Under no circumstances shall a scratch specimen be contaminated with a cleaning solvent. Care shall be taken that cleaning solvents do not contact the specimen.

10. Calibration and Standardization

10.1 Scratch machine, data acquisition system, and any associated electronic equipment shall be maintained at a constant temperature (±2°C) for a period of at least 24 hours prior to and during testing. The test equipment shall be located in an environment with the standard laboratory atmosphere as specified in Practice D618.

10.2 Prior to conducting any test, verification, or calibration, or a combination of the three, the scratch machine and associated electronic equipment shall be powered on and allowed to warm up for a period of not less than thirty minutes.

10.3 Before any test, the accuracy of the load and position sensors shall be verified. Sensors for the normal load and tangential force shall operate within an accuracy of ±0.1 N. Position sensors shall also be checked against standards to assess their accuracy (±1 µm). Should the accuracy of the load and position sensors be found out of specification, calibration must be performed.

10.4 For calibration, precision weights shall be used to calibrate load sensors while standard gauge blocks or feeler gauges can be used to calibrate position sensors. All calibration tools, including weights and gauges, shall be of known and certified accuracy. After calibration, the accuracy of the load and position sensors must be re-verified prior to performing tests.

11. Conditioning

11.1 To conduct scratch tests under the standard laboratory atmosphere, the conditioning practice, Procedure A as specified in Practice D618 shall be followed. For other testing conditions, users shall refer to Practice D618 for the recommended conditioning procedures.

11.2 Prior to the execution of the tests, the surface of the specimen and the scratch stylus are to be inspected for any contaminants and cleaned if necessary. Only cleaners that do not alter the test material and its surface characteristics shall be used for cleaning specimens and the scratch stylus. Organic solvents may be used on the metal stylus. If the specimen is found to be dirty, it may be cleaned using compressed air or similar. Cleaning specimens with liquids is not recommended as cleaners may leave residues that affect the scratch test. Under no circumstances shall an organic solvent be used to clean polymer samples prior to testing. If a cleaner is used then the cleaner must be known to not affect the chemical structure of the specimen.

12. Procedure

12.1 Mark the intended start and end positions of the scratch path on the sample using a fine-point permanent marker or paint pen (optional).

12.2 Place the specimen on the test stage and secure it with lockable clamps. Make sure that the specimen is flat and the surface is clean. The specimen should be in complete contact with the base (work surface) of the machine. Any gaps between the bottom of the specimen and the work surface will cause errors in the analysis. Move the scratch stylus to one end of the specimen where the start position of the scratch path is. The scratch tip should be positioned about 1 mm above the test specimen for consistency. Check to confirm that the stylus tip is clean and free of damage.

12.3 If scratch tests are to be conducted at temperatures other than the room temperature (23 ± 2°C), an environmental chamber shall be used to maintain the stylus and the specimen at the desired temperature. The stylus and specimen shall be conditioned in the environmental chamber for not less than thirty minutes, prior to testing.

12.4 Ensure that load and position sensing and data acquisition systems are operational when real-time data are to be collected.

12.5 Configure the scratch machine to perform the desired test by inputting the necessary parameters such as scratch rate, load, and data capture rate.

12.6 Begin the scratch process.

12.7 Examine the scratch groove of the test specimen under a calibrated microscope, or a profilometer, or both, and quantify the scratch width, depth, and/or other predefined scratch damage. A flatbed scanner may also be used for this purpose.

12.8 When using Test Mode A and failure is observed, the point of the first occurrence along the scratch path shall be noted. This can be accomplished visually or through the

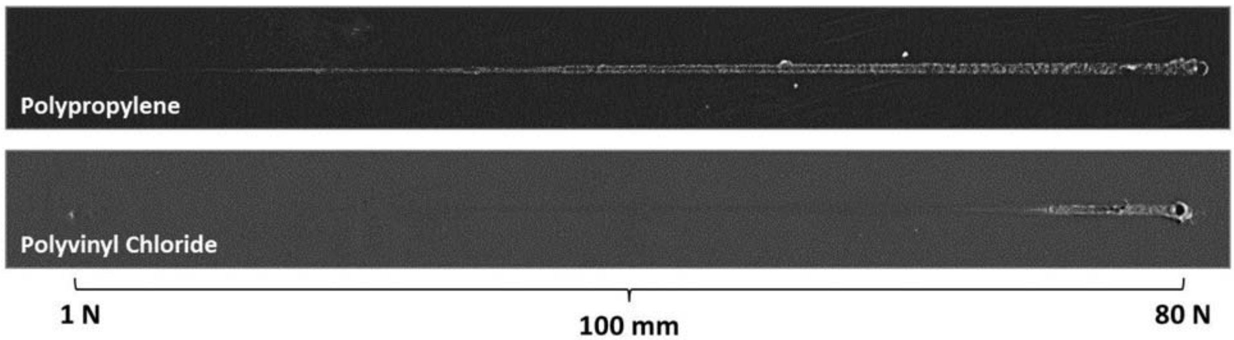

FIG. 4 Digitally Scanned Images of Samples of Polypropylene and Polyvinyl Chloride Subjected to Test Mode A Under a Progressive Load Range of 1-80 N

assistance of optical instruments and image analysis tools, such as an ASV (3.1.1). Correspondingly, the critical normal load for failure shall be determined and used for material comparison and ranking. To illustrate the difference in surface damage, Fig. 4 shows that polypropylene has significantly less resistance than polyvinyl chloride when onset of whitening is considered as the point of failure subjected to Test Mode A under the same progressive load range of 1-80 N.

13. Calculation or Interpretation of Results

13.1 Scratch width, or depth, or both, can be quantified with a flat-bed scanner, optical microscope or other appropriate profile analysis instruments, as specified in 8.8 of Test Method G171. The width and depth measured shall provide critical dimensions for analyzing the scratch path. It shall be noted, however, that comparing the scratch width provides more consistent results than the scratch depth, as the latter tends to fluctuate significantly even under constant loads. Should there be a need to use scratch depth as a basis of comparison, users must clearly indicate how the scratch depth is measured, based on the definition provided in 3.1.6.

13.2 The critical normal load may be used to rank the scratch performance of samples. A higher critical normal load indicates higher material performance as it indicates that higher force was required to achieve the point of failure. When materials are ranked in this manner the failure criteria used for the analysis should also be stated in the results.

13.3 For Test Mode A, the critical load for a failure event, F_c, can be estimated based on the linear relationship between the applied normal load and the scratch distance:

$$F_c = \frac{d}{D} \cdot (F_f - F_0) + F_0 \quad (1)$$

where:

d = distance measured to the failure event from the beginning of the scratch in millimeters,
D = total scratch length in millimetres, and
F_f and F_0 = final and initial applied normal loads, respectively, in Newtons.

More precise results can be obtained by simply checking the actual applied load at the point of failure from the scratch machine data file.

13.4 Incorporating the depth and load sensing option to the scratch machine allows the instantaneous or real time data such as scratch depth, tangential force, and normal load to be captured during the scratch process and these data can then be plotted graphically for study. As an example, curves representing the applied normal load, and the measured tangential force along the scratch path during the scratch process are shown in Fig. 5.

14. Report

14.1 The test report shall include information on the tip material, test specimens, test conditions, and all measured parameters. The average values of the five measurements shall be reported with standard deviation.

14.2 *Critical normal load*—The method used to quantify point of failure shall be reported. Whether by visual inspection, image evaluation analysis, or microscopy, the same method shall be used to maintain consistency and facilitate comparison.

NOTE 1—The critical normal load can either be read off the force profile from the data acquired or by measuring the distance of the failure point from scratch initiation and then calculating the normal load from the distance obtained. Fig. 6 shows how the critical normal load for whitening of various polypropylene systems can be represented graphically and used for comparison; the value for each material is an average of five scratch tests.

14.3 *Normal load*—For materials that do not exhibit whitening as mentioned in 3.1.11, the magnitude of the normal load that corresponds to a predetermined scratch width, as defined in 3.1.8 shall be reported.

NOTE 2—The predetermined value for the scratch width may differ with materials and applications. Plots of normal loads against scratch widths like Fig. 7 can be generated and the normal loads can be read off at the predetermined scratch width. Applying this approach to different materials allows a quantitative comparison of their scratch resistance.

NOTE 3—Materials will exhibit a quadratic relationship between the normal load and scratch width. In any case where there is a significant deviation from the quadratic relationship, it may indicate the occurrence of severe fracture, spalling or delamination and such an anomaly shall be reported.

14.4 *Scratch width and depth*—Residual and instantaneous (if available) measurements shall be reported, along with the method used for the measurement.

NOTE 4—Due to the different sensitivity of each method, measurements obtained may differ slightly. Though it may be generally accepted that the

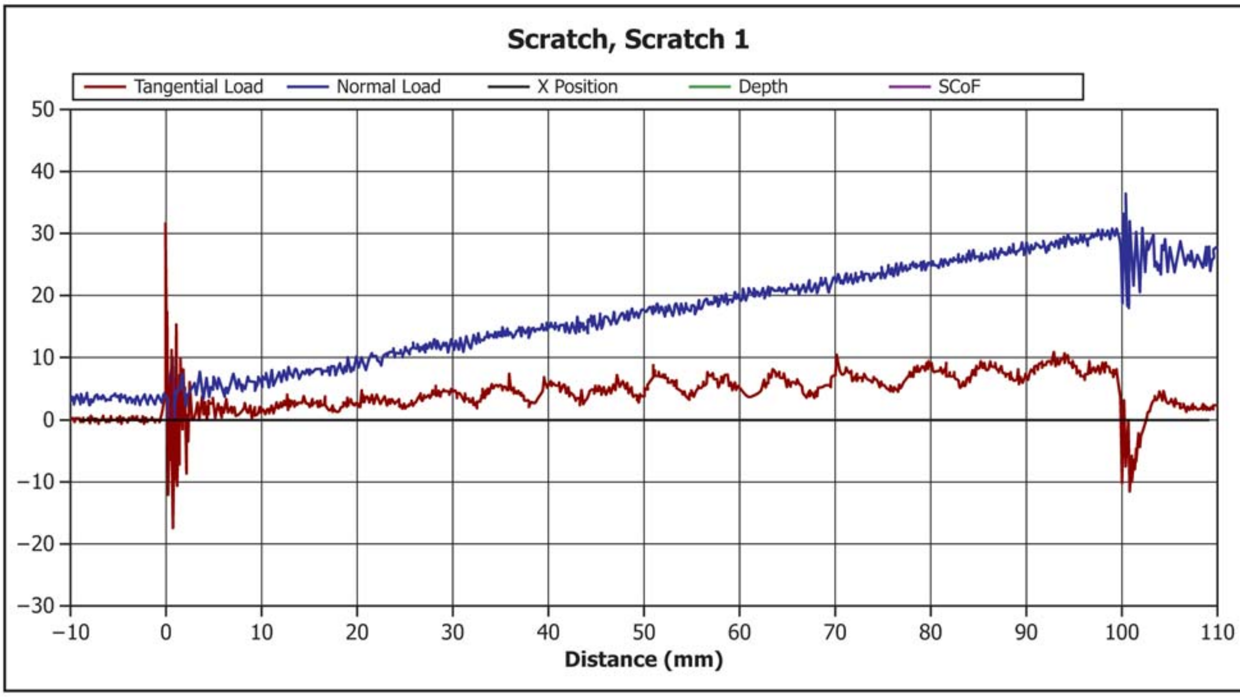

FIG. 5 Sample Data Showing Normal Load and Tangential Force Curves for a Polypropylene-Based Specimen Subjected to Test Mode A Under a Progressive Normal Load of 1-30 N. A Low Pre-Loading was Applied at -10 mm to Allow for Acceleration of Scratch Tip to Move from Static to 100 mm/S.

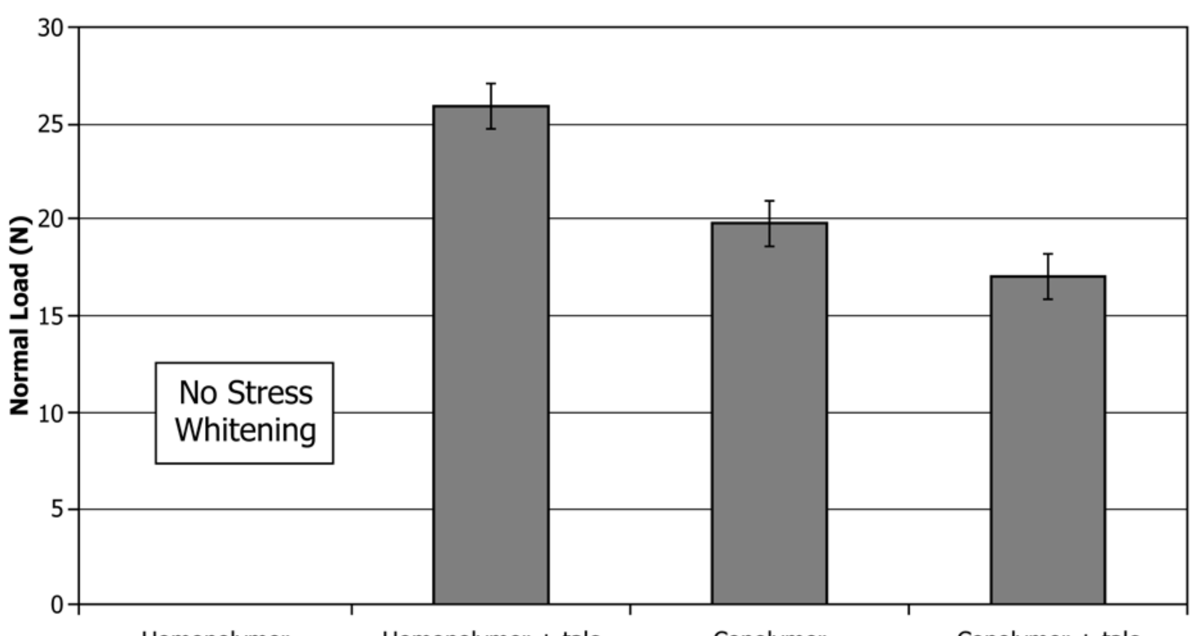

FIG. 6 Critical Normal Load for the Onset of Whitening of Various Polypropylene Systems

profilometer gives the most sensitive measurement, contact-type profilometers may damage the scratch groove during measurements. In the absence of profile analysis instruments, scratch widths can be measured using optical microscopes or flatbed scanners.

14.5 *Tangential Force*—At the point where whitening occurs shall be reported whenever the data is available.

14.6 *Scratch coefficient of friction,* as defined in 3.1.5, shall be reported for Test Mode B.

NOTE 5—Scratch hardness may be determined graphically from a plot of normal load, P, versus the projected scratch area ($\pi w^2/4$), where w is the scratch width (see Fig. 8).

15. Precision and Bias

15.1 To assess the precision and bias of the test method on the basis of repeatability and reproducibility, the two test modes (A and B) shall be used. The material chosen for the

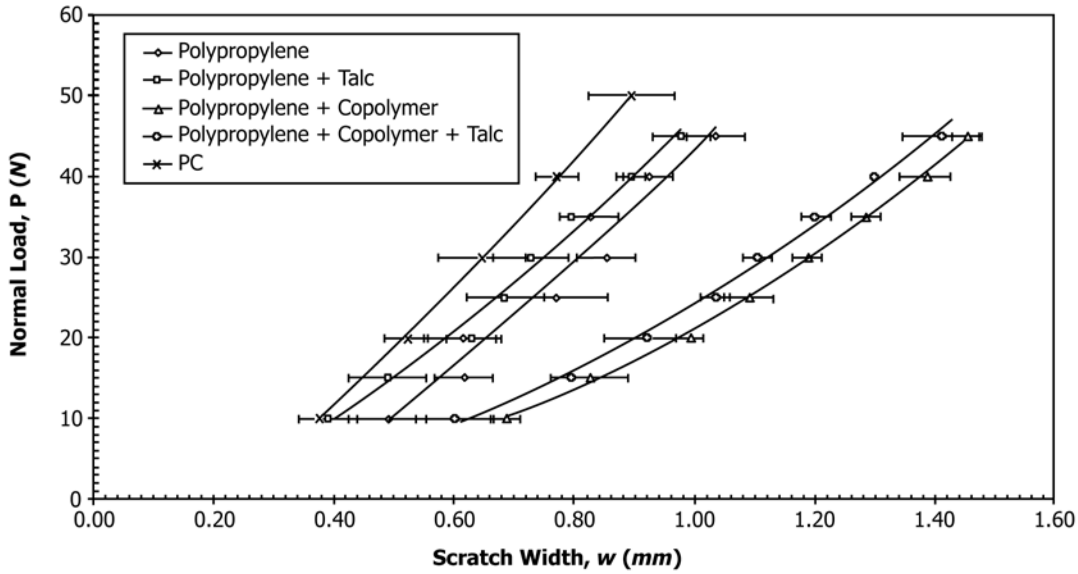

FIG. 7 Variation of Scratch Width with Normal Load

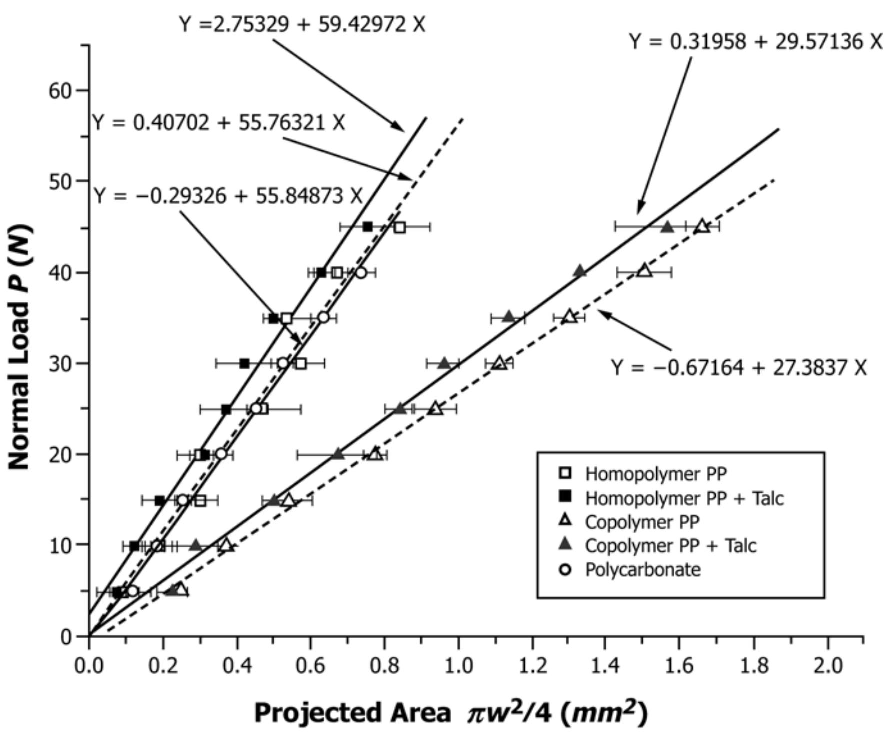

FIG. 8 Graphical Method of Obtaining Scratch Hardness

assessment exercise is polypropylene. The precision of test data are determined and expressed in accordance with Practice E177.

15.2 *Test Mode A (Increasing Load Test)*—Using Test Mode A where the normal load increases from 2 to 50 N, the critical normal load for stress whitening, as defined in 3.1.2 and 5.4 was adopted as the key scratch parameter to examine the repeatability and reproducibility of the test method. To determine the critical point for the onset of stress-whitening, an image capturing equipment, VIEEW (ATLAS) was utilized with a consistent set of light and grey-scale settings.

15.2.1 *Repeatability*—Table 1 is based on two test runs by a single operator. For each test run, the specimen was prepared at one source. Table 1 is presented on the basis of a test result being the average of three samples. The test runs were conducted by the same operator under the same operating conditions using the same machine on the same day.

TABLE 1 Repeatability Data—Critical Normal Load for Stress Whitening (A Single Operator)

Test Run	Average	S_r[A]	I_r[B]
1	6.79	±0.26	±0.73
2	6.61	±0.38	±1.07

[A] S_r = within-laboratory standard deviation of the average.
[B] I_r = 2.83 S_r.

15.2.2 *Reproducibility*—Table 2 is based on a round-robin test involving three operators. For each test run, the specimen was prepared at one source. Table 2 is presented on the basis of a test result being the average of five samples. The round-robin test was conducted by three operators under the same operating conditions using the same machine on the same day.

TABLE 2 Reproducibility Data—Critical Normal Load for Stress Whitening (Three Operators)

Operator	Average	S_r[A]	I_r[B]
I	6.64 N	±0.26 N	±0.74 N
II	6.72 N	±0.18 N	±0.52 N
III	6.80 N	±0.20 N	±0.57 N

[A] S_r = within-laboratory standard deviation of the average.
[B] I_r = 2.83 S_r.

15.3 *Test Mode B (Constant Load Test)*—On the repeatability and reproducibility of the test method using Test Mode B, the scratching coefficient of friction, as discussed in 3.1.5, will be used as a basis of evaluation.

15.3.1 *Repeatability*—Table 3 is based on two test runs by a single operator. For each test run, the specimen was prepared at one source. Table 3 is presented on the basis of a test result being the average of three samples. The test runs were conducted by the same operator under the same operating conditions using the same machine on the same day.

TABLE 3 Repeatability Data—Scratching Coefficient of Friction (A Single Operator)

Test Run	Average	S_r[A]	I_r[B]
1	0.430	±0.012	±0.034
2	0.433	±0.014	±0.040

[A] S_r = within-laboratory standard deviation of the average.
[B] I_r = 2.83 S_r.

15.3.2 *Reproducibility*—Table 4 is based on a round-robin test involving three operators. For each test run, the specimen was prepared at one source. Table 4 is presented on the basis of a test result being the average of five samples. The round-robin test was conducted by three operators under the same operating conditions using the same machine on the same day.

TABLE 4 Reproducibility Data—Scratching Coefficient of Friction (Three Operators)

Operator	Average	S_r[A]	I_r[B]
I	0.433	±0.010	±0.028
II	0.434	±0.010	±0.028
III	0.433	±0.005	±0.014

[A] S_r = within-laboratory standard deviation of the average.
[B] I_r = 2.83 S_r.

15.4 *Bias*—There are no recognized standards by which to estimate bias of this test method using the two test modes.

16. Keywords

16.1 critical load; polymer; ranking; rising load; scratch; scratch resistance; scratch visibility; whitening