



Designation: **D7187—15 D7187 – 20**

# Standard Test Method for Measuring Mechanistic Aspects of Scratch/Mar Behavior of Paint Coatings by Nanoscratching<sup>1</sup>

This standard is issued under the fixed designation D7187; 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 ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This test method covers ~~the~~ nanoscratch method for determining the resistance of paint coatings on smooth flat surfaces to scratch/mar.

1.2 ~~Previous~~Other methods used in scratch/mar evaluation ~~first~~ physically scratch or mar a sample's surface with single or multiple contact cutting, and then use visual inspection to assign a ranking. It has been recognized that loss of appearance is mainly due to surface ~~damages created~~. ~~The philosophy of this method is to damage created~~. This method quantitatively and objectively ~~measure~~measures scratch/mar behavior by making the evaluation process two steps with emphasis on surface ~~damages~~damage. Step one is to find the relationship between damage shape and size and external input (such as forces, contact geometry, and deformation). Step two is to relate damage shape and size to visual loss of luster. The first step is covered by this method; in addition, a survey in the appendix provides an example of an experiment to relate the damage to the change in luster.

1.3 There are three elementary deformation mechanisms: elastic deformation, plastic deformation and fracture; only the latter two ~~both~~ contribute significantly to mar. This method evaluates scratch/mar based on the latter two damage mechanisms.

1.4 Although this standard was developed for paint coatings, it can also be applied to other types of similar polymer-based coatings, for example, lacquers, varnishes, glazes and other decorative and protective layers deposited on hard substrates.

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

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

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

## 2. Referenced Documents

2.1 *ASTM Standards:*<sup>2</sup>

[D609 Practice for Preparation of Cold-Rolled Steel Panels for Testing Paint, Varnish, Conversion Coatings, and Related Coating Products](#)

[D823 Practices for Producing Films of Uniform Thickness of Paint, Coatings and Related Products on Test Panels](#)

[D1005 Test Method for Measurement of Dry-Film Thickness of Organic Coatings Using Micrometers](#)

[D1044 Test Method for Resistance of Transparent Plastics to Surface Abrasion by the Taber Abraser](#)

[D3363 Test Method for Film Hardness by Pencil Test \(Withdrawn 2020\)](#)<sup>3</sup>

[D3924 Specification for Standard Environment for Conditioning and Testing Paint, Varnish, Lacquer, and Related Materials](#)

[D5178 Test Method for Mar Resistance of Organic Coatings](#)

[D6037 Test Methods for Dry Abrasion Mar Resistance of High Gloss Coatings](#)

[D6279 Test Method for Rub Abrasion Mar Resistance of High Gloss Coatings](#)

<sup>1</sup> 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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<sup>2</sup> For referenced ASTM standards, visit the ASTM website, [www.astm.org](#), or contact ASTM Customer Service at [service@astm.org](#). For *ASTM Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

<sup>3</sup> The last approved version of this historical standard is referenced on [www.astm.org](#).

[D7027 Test Method for Evaluation of Scratch Resistance of Polymeric Coatings and Plastics Using an Instrumented Scratch Machine](#)

[D7091 Practice for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to Ferrous Metals and Nonmagnetic, Nonconductive Coatings Applied to Non-Ferrous Metals](#)

[G171 Test Method for Scratch Hardness of Materials Using a Diamond Stylus](#)

### 3. Summary of Test Method

3.1 This test method is based on representative samples of the paint film being scratched using a nanoscratch instrument. From information ~~received~~generated during a scratch test, values for plastic resistance (PR) and fracture resistance (FR) can be determined. From these values, the mechanistic aspects of scratch/mar behavior of the coating can be compared.

~~3.2 From these values of plastic resistance and fracture resistance, the mechanistic aspects of scratch/mar behavior of the coating can be subsequently compared.~~

### 4. Significance and Use

4.1 This test ~~attempts to address two major drawbacks~~addresses two limitations in existing mar tests such as Test Methods [D1044](#), [D3363](#), [D5178](#), [D6037](#), and [D6279](#), namely:

4.1.1 Measured damage is caused by hundreds of contacts with differing contact geometries making it difficult or impossible for mechanical quantities (force, displacement) at the contact points to be reliably determined.

4.1.2 The damage is evaluated using subjective visual assessments, which provide only a qualitative sense of wear with little information about mar mechanisms.

4.2 This test provides a quantitative assessment of a paint coating's mechanistic aspects of scratch/mar behavior in various conditions. The ability to control testing variables such as ~~rate~~loading rate, speed, and temperature allow the study of the scratch/mar behavior in a variety of environments.

4.3 This test method is particularly suitable for measurement of paint coatings on laboratory test panels.

4.4 The accuracy and precision of scratch/mar performance may be significantly influenced by coating surface nonuniformity~~non-uniformity~~ and irregularities.

4.5 A correlation has been observed between good mar resistance in field studies and a combination of high ~~Plastic Resistance~~plastic resistance and high ~~Fracture Resistance~~fracture resistance. When coatings have had either high ~~Plastic Resistance~~plastic resistance and low ~~Fracture Resistance~~fracture resistance, or low ~~Plastic Resistance~~plastic resistance and high ~~Fracture Resistance~~fracture resistance, there have been contradictory results in field studies.

4.6 Mar resistance characterizes the ability of the coating to resist light damage. The difference between mar and scratch resistance is that mar is related to only the relatively fine surface scratches which spoil the appearance of the coating. The mechanistic aspects of mar resistance depend on a complex interplay between visco-elastic and thermal recovery, yield or plastic flow, and micro-fracture. Polymers are challenging because they exhibit a range of mechanical properties from near liquid through rubber materials to brittle solids. The mechanical properties are rate and temperature dependent and visco-elastic recovery can cause scratches to change with time. One such test for evaluating polymeric coatings and plastics is Test Method [D7027](#).

4.7 Since this method measures mechanical qualities, such as forces and displacements (deformations) during the damage making process, rate dependence, temperature dependence, and visco-elastic-plastic recovery can be further investigated and visual impacts of damage can be related to deformation mechanisms.

### 5. Apparatus

5.1 *Paint Application Equipment*, as described in Practices [D609](#) and [D823](#).

5.2 *Nanoscratch Instrument*, consisting of an instrument with a well-defined indenter, which translates perpendicular to the coating surface and has the capacity to produce an instrumented scratch of controlled and variable normal force and continuously measured displacement during testing. The normal force ~~must~~shall be feedback controlled, in order to quickly respond to variations in surface morphology. The force of the instrument should have a maximum normal force of at least 50 mN (~~mN should be read as milli-Newtons~~) with a resolution of at least 0.1 mN. 50 mN ± 0.1 mN. The maximum tangential force, if measured, should be at least 50 mN ~~with a resolution of at least ± 0.5 mN.~~ The range of the displacement sensors should be at least 50 ~~200~~ μm with a resolution of at least 20 nm. Displacement and tangential force response of the coating should be measured with a high data acquisition rate, such as a maximum of ~~five~~5 μm between data points.

5.3 *Suggested Range for Testing Parameters:*

5.3.1 Indenter size should range from ~~±1 μm~~ to ~~±100 microns~~100 μm and should be spherical in geometry. Indenter material should be diamond.

5.3.2 The scratch should be applied at a rate of ~~0.50.5 mm~~ to ~~40 millimetres~~10 mm per minute.

5.3.3 The loading rate of the normal force should be applied at ~~55 mN~~ to ~~200 mN~~200 mN per minute.

5.3.4 The scanning preload should be conducted with an applied force of  $0.10 \pm 0.01$  mN.

5.4 The following is an example of one particular application of the test ranges. This example is based on automotive clear coats on a metal substrate.

5.4.1 Indenter size of  $2 \mu\text{m}$ .

5.4.2 Scratch rate of  $3 \text{ mm per minute}$ .

5.4.3 Loading rate of  $40 \text{ mN per minute}$ .

5.4.4 Scanning preload of  $0.2 \text{ mN}$ .

5.4.5 Data acquisition rate of  $3 \mu\text{m}$  between data points.

NOTE 1—To optimize test parameters for a particular coating, it should be remembered that experiments may need to be conducted as different combinations of applied load and indenter radius will cause differing damage in polymeric coatings. A smaller indenter radius (sharper tip) will tend to cut the coating and apply a higher contact pressure, whereas a larger indenter radius (blunter tip) will tend to tear the coating and apply a lower contact pressure.

## 6. Test Specimen

6.1 The substrate for the paint coating should be a smooth, plane, rigid surface, such as those specified in Practices D609 and D823.

6.2 The thickness of the coating being tested, determined in accordance with either Test Methods D1005; or D7091, should be uniform within  $500 \text{ nm}$ . In order to minimize the effect of the substrate for maximum accuracy, the penetration depth should not exceed one-half the  $5\%$  of coating thickness.

6.3 At least three scratches should shall be performed on each test specimen.

6.4 The surface of the specimens should shall be free of any dirt and oils. Care should be taken when cleaning samples: solvents should not be used as they may modify the surface properties of polymer-based coatings. For removing dust, it is recommended to blow off particulates with compressed air from a clean source (without oil contamination).

6.5 The specimen size should be sufficient to be adequately secured to the nanoscratch instrument, but not so small as to interfere with the movement of the indenter tip or its supporting cantilever.

NOTE 2—It is recommended that substrates with similar compliances be used when comparing different coatings.

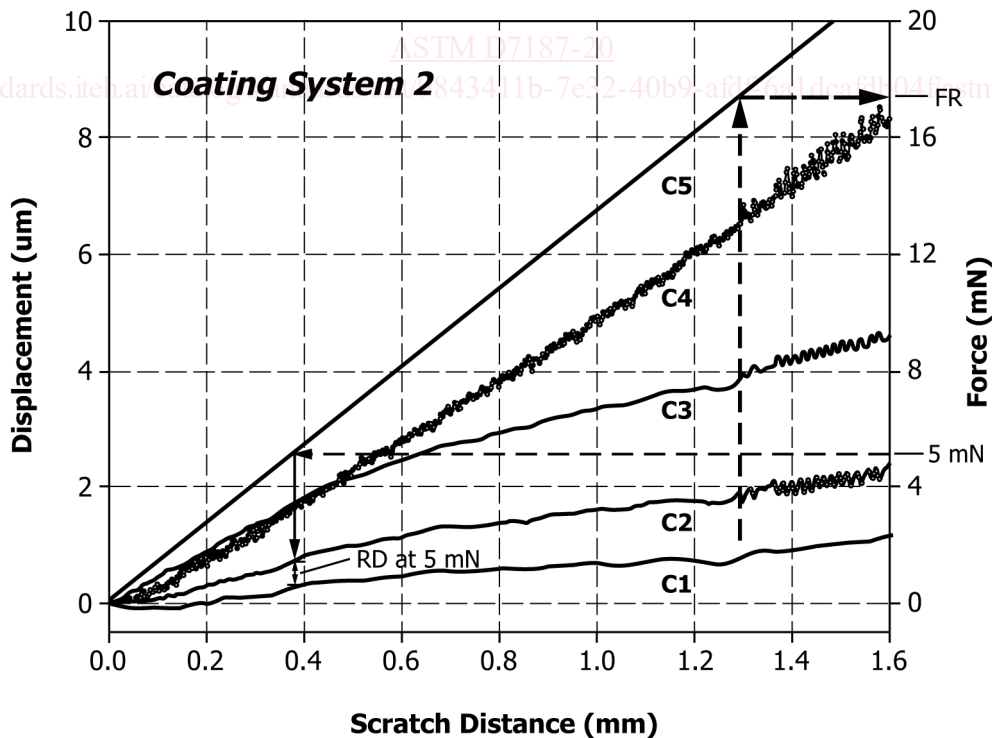


FIG. 1 Example - Typical Data from a Nanoscratch Experiment C1—Vertical Displacement of the Indenter During the Pre-scan C2—Vertical Displacement During Post-scan C3—Vertical Displacement During Scratch C4—Tangential Force C5—Applied Normal Force Test (1)

## 7. Conditioning

7.1 Cure the coated test specimens under conditions agreed upon between the purchaser and seller that reflect the conditions of curing of the paint in actual service.

7.2 Condition and test the test specimens at  $23 \pm 2^\circ\text{C}$  ( $73.5 \pm 3.5^\circ\text{F}$ ) and a relative humidity of  $50 \pm 5\%$  for at least 24 h, unless the purchaser and seller agree on more suitable test characteristics, as specified in the Standard Atmosphere of Specification **D3924**.

## 8. Procedure

8.1 Secure the specimen to the moveable stage on the instrument with the surface to be measured located perpendicularly to the indenter tip. Ensure the panel is held rigidly to the stage and cannot be moved by the action of the subsequent scratch test.

8.2 Carefully move this area under the indenter and bring the indenter tip close to the sample surface.

8.3 The complete scratch test consists of three distinct steps. In all three steps, the indenter follows the exact same path across the sample surface.

NOTE 3—A set of sample test parameters can be found in 5.4.

8.3.1 Perform a prescan to measure the topography of the undamaged coating. Apply the lowest load that the instrument can apply but that makes no permanent damage. The prescan, scratch, and postscan ~~should all~~ **must** be performed on the same line.

8.3.2 Instruct the instrument to begin making a scratch to produce damage to the coating. Allow the instrument to ramp to the desired normal force at a controlled rate. At the end of the scratch, return the indenter tip to its starting position at the beginning of the scratch.

8.3.3 ~~Perform~~ **Without delay perform** a postscan, where the indenter tip is scanned along the scratch, measuring the residual topography of the damaged area. This should be done with the lowest load the instrument can apply.

NOTE 4—Prescan and postscan should only be used if the instrument has force feedback control, otherwise significant error may be incurred.

NOTE 5—The prescan and postscan need to be conducted consistently (with the same scanning parameters) before and after the scratch load is applied. This is done to accurately measure recovery aspects since these aspects will vary with time.

8.4 The complete scratch test ~~should~~ **shall** be repeated ~~two~~ **two** more times at different locations so that there are a total of ~~three~~ **three** scratches per test panel.

8.5 ~~Typical results of~~ **Results of typical data from** a nanoscratch test are presented in **Fig. 1**<sup>4</sup>. The graph consists of five curves labeled ~~1-C<sub>1</sub>~~ through ~~5-C<sub>5</sub>~~. If needed, ~~required~~ **correct** the data by curve fitting so that zero indenter penetration and residual depth (RD) corresponds to zero applied normal force.

8.5.1 Curve 1 (**C<sub>1</sub>**) shows the topography of the unscratched surface along the scratch path. It is a measure of the vertical displacement of the indenter tip during a low (~0.2 mN) constant load prescan.

8.5.2 Curve 2 (**C<sub>2</sub>**) shows the topography of the damaged surface along the scratch path immediately after the scratch test was concluded. It is a measure of the vertical displacement of the indenter tip during a low (~0.2 mN) constant load scan through the completed scratch.

8.5.3 Curve 3 (**C<sub>3</sub>**) shows the vertical displacement of the indenter tip during the scratching process.

8.5.4 Curve 4 (**C<sub>4</sub>**) shows the tangential force that arises between the coating and the indenter tip.

8.5.5 Curve 5 (**C<sub>5</sub>**) shows the applied normal force on the coating surface.

## 9. Calculations

9.1 From analysis of the ~~Force/Displacement~~ **force/displacement** versus ~~Scratch Distance~~ **scratch distance** plot produced (**Fig. 1**), plots of various ~~quantities~~ **properties** relating to the mechanical behavior of the coating versus scratch distance can be generated:

9.1.1 ~~The penetration~~ **Penetration** depth (PD) of the indenter under the applied normal force can be calculated by subtracting the surface topography measured ~~from~~ **during** the prescan, ~~Curve 1,~~ **curve 1 (C<sub>1</sub>)**, from the displacement measured during the scratch, ~~Curve 3.~~ **curve 3 (C<sub>3</sub>)**.

$$PD = C_3 - C_1$$

where PD means ~~Penetration Depth~~ **penetration depth**, and **C<sub>3</sub>** and **C<sub>1</sub>** correspond to ~~Curves~~ **curves** 3 and 1 respectively.

9.1.2 The magnitude of residual depth (RD), otherwise known as permanent plastic deformation, to the coating can be calculated by subtracting the surface topography before the scratch, ~~Curve 1,~~ **curve 1 (C<sub>1</sub>)**, from the topography after the scratch, ~~Curve 2.~~ **curve 2 (C<sub>2</sub>)**.

$$RD = C_2 - C_1$$

<sup>4</sup> The boldface numbers in parentheses refer to the list of references at the end of this test method.

9.1.3 The Elastic recovery (ER) of the coating is the difference between the displacement during the scratch, Curve 3, curve 3 (C<sub>3</sub>), and the surface topography after the scratch, Curve 2, isurve 2 (C<sub>2</sub>) the elastic recovery (ER) of the coating.

$$ER = C_3 - C_2$$

$$ER = C_3 - C_2$$

9.1.4 The ratio of tangential force, Curve 4, curve 4 (C<sub>4</sub>), to the normal force, Curve 5, curve 5 (C<sub>5</sub>), is a form of the friction coefficient (C<sub>f</sub>).

$$C_f = C_4/C_5$$

NOTE 5—The prescan and postscan need to be conducted consistently (with the same scanning parameters done within less than 10 minutes) before and after the scratch load is applied. This is done to accurately measure recovery aspects since these aspects will vary with time.

9.2 Plastic resistance (PR) at a particular normal force can be calculated by dividing the normal force by the magnitude of the permanent damage at that normal force before fracture occurs. Selecting the spot for measurement to be at a higher applied normal force results in values that reflect a more true plastic resistance. This gives a value for plastic resistance that is relatively constant that is in units of force per unit of damage depth, or mN/μm.

$$PR = F_N/RD$$

where:

PR = plastic resistance,

F<sub>N</sub> = the normal force in mN, and

RD = permanent plastic deformation or residual depth in microns

RD = permanent plastic deformation or residual depth in μm.

NOTE 6—Only at very low normal force values does the plastic resistance differ radically. In our tests, we selected the measurement point to be at 5 mN. In the case of Fig. 2, the material has fractured at 5 mN-17 mN so plastic resistance should be measured at a lower force. force (measurement point selected was 5 mN). Plastic resistance values should be evaluated in the area of the curve that is relatively constant and in the area before fracture occurs.

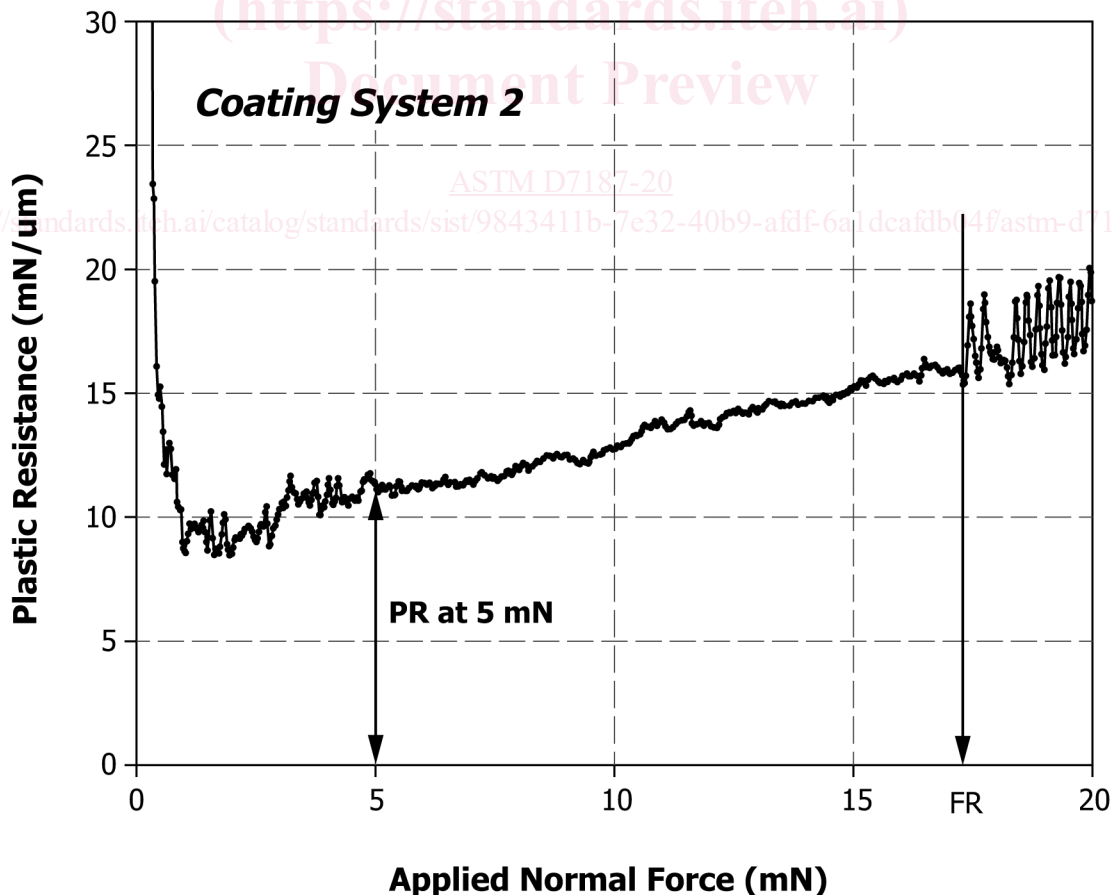


FIG. 2 Example - Variation of Plastic Resistance (PR) with Respect to Applied Normal Force. Note that the constant plastic resistance value at higher (greater than 3 mN) applied loads. FR refers to the Fracture resistance, or critical load. Force (2)

9.3 Fracture resistance (FR) can be determined by locating the point where normal force, tangential force, penetration depth of the indenter and permanent damage begin to fluctuate wildly. This is the point where the first fracture occurs. Any subsequent increase in normal force only leads to increased fracture. This mechanical quantity is known as the *critical load* and has units of mN.

NOTE 7—Onset of the fracture can also be identified with an integrated video microscope (with at least 1000× magnification) or Atomic Force Microscope. In this case, calibrate the position of the microscope with the scratch tip prior to the start of the scratch test.

9.4 Plastic deformation and fracture are the two damage mechanisms that will have an effect on the coating performance. As shown in Fig. 3 a and b, the morphology of these two types of deformation is quite different. This difference in morphology is what has the most profound influence on the appearance of the coating. Plastic deformation is calculated in 9.1.2 and is also known as the magnitude of permanent damage or residual depth (RD).

9.5 Data for several coatings may be compared using a graph of ~~Plastic Resistance versus Fracture Resistance~~, plastic resistance versus fracture resistance, as shown in Fig. 4.

9.6 For some coating types, it may be of interest to calculate the plastic resistance based on the width of the scratch. In this case, the plastic resistance can be defined as the ratio of applied normal load divided by the width of the scratch at that point along the scratch. This methodology is similar to that described in Test Method G171 for the measurement of scratch hardness. It requires a means of directly measuring the scratch width; this can be achieved by microscopy or by stylus profilometry.

## 10. Report

10.1 Report the following information:

10.1.1 Mean and range of fracture resistance (FR) and plastic resistance (PR) or residual depth (RD) values, and where these values are measured (~~5 mN in our example~~), measured, obtained for each sample.

10.1.2 Type of coating, substrate and coating techniques used.

10.1.3 Time and temperature of sample conditioning.

10.1.4 Indenter size and shape.

10.1.5 Applied load range (minimum and maximum), loading rate and scanning force.

10.2 ~~An example of reported test parameters can be found in 5.4.~~

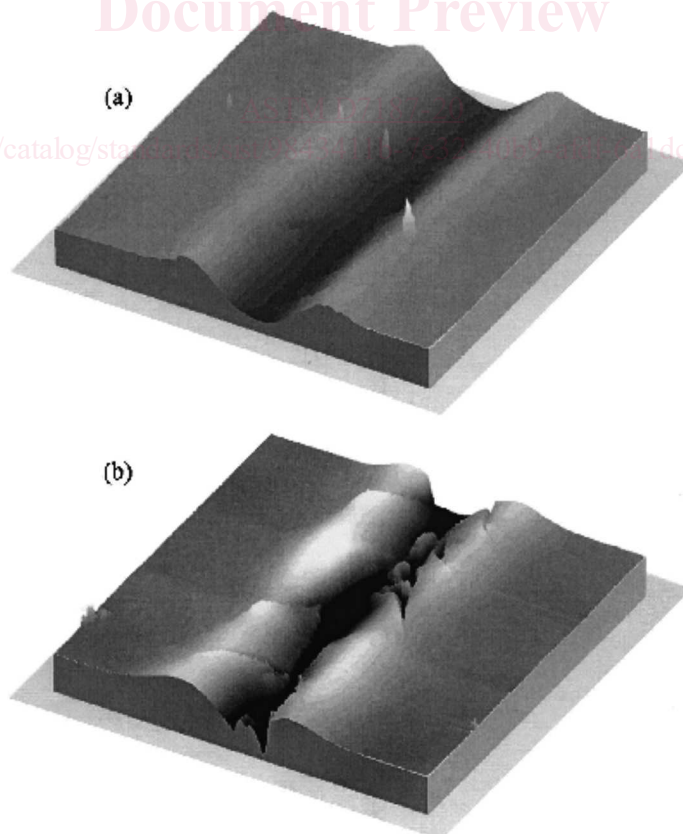


FIG. 3 AFM Images of a Scratch both before Fracture (a) and after Fracture (b)

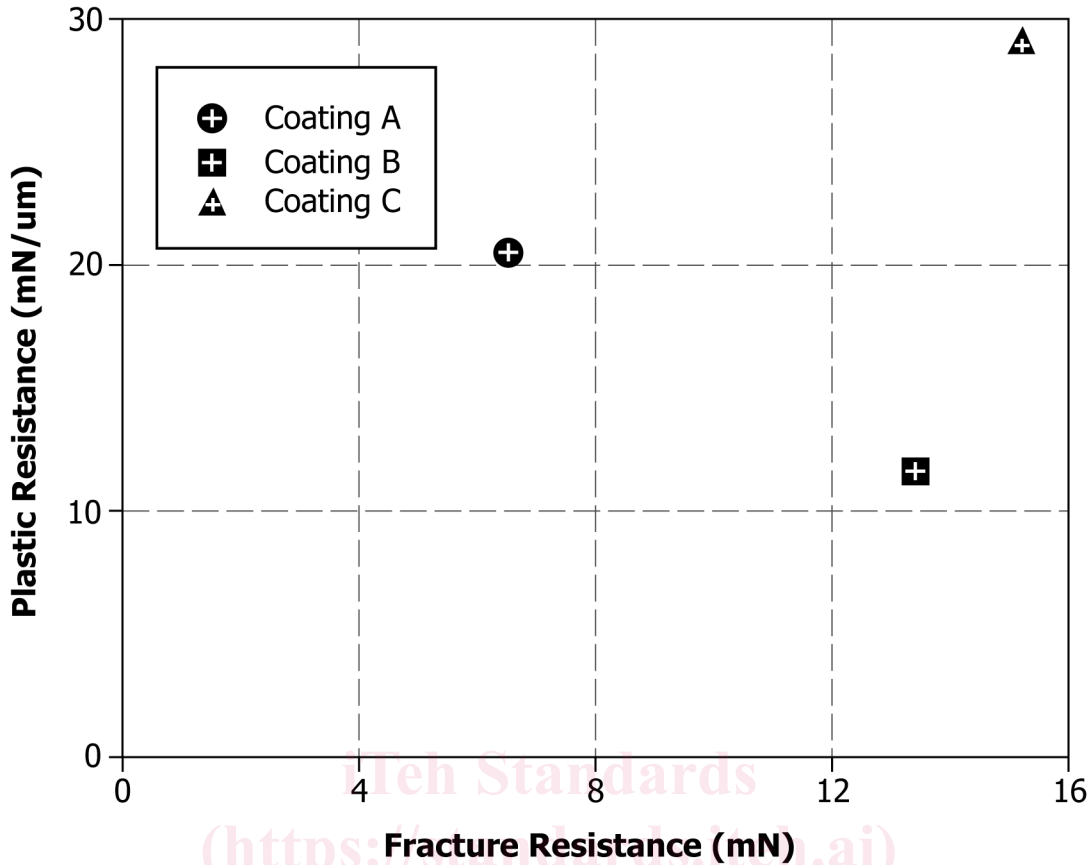


FIG. 4 Example - Mar Resistance of Coatings A, B and C Distinguished According to Their Fracture Resistance and Plastic Deformation Resistance B, and C

11. Precision and Bias

11.1 Precision—Six samples, each of three automotive clearcoats with differing chemistry, named System 1, 2, and 3, were tested at Dupont Marshall Labs, CSM Instruments and FPL for repeatability and reproducibility and discrimination. Statistically, the rule of thumb is at least 30 data points are needed to assess variability. The data set with three laboratories, three different samples (systems) and six measurements each, yields a total of 54 results for analysis and is used to demonstrate the method’s repeatability and reproducibility. In all cases, the CSM Instruments Nano-Scratch Tester (NST) was used. The software MINITAB was utilized to perform the statistical analysis.

TABLE 1 Statistical Results of Fracture Resistance

Materials	Mean	Sr	SR	r	R
System 1	8.8556	0.2685	0.3290	0.7518	0.9213
System 2	18.9111	0.6241	1.3024	1.7476	3.6467
System 3	31.5822	1.0954	1.8195	3.0671	5.0946

TABLE 2 Statistical Results of Residual Deformation

Materials	Mean	Sr	SR	r	R
System 1	0.2087	0.0199	0.0243	0.0557	0.0680
System 2	0.4150	0.0206	0.0296	0.0576	0.0828
System 3	0.1346	0.0276	0.0298	0.0773	0.0834

11.1.1 Fracture Resistance:

11.1.1.1 Table 1 shows the statistical results of fracture resistance. Here Sr is the average value of standard deviation measured by the three individual groups, and SR is the overall standard deviation of all 18 samples from the three groups. Values of r and R are 2.8 times of Sr and SR, respectively. Repeatability is characterized by the values of Sr and r. Reproducibility is characterized by the values of SR and R.