Designation: G171 – 03 (Reapproved 2009)$^{\varepsilon 2}$

Standard Test Method for
Scratch Hardness of Materials Using a Diamond Stylus[1]

This standard is issued under the fixed designation G171; 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.

ε^1 NOTE—Deleted erroneous reference in 8.4 editorially in May 2009.
ε^2 NOTE—Reference to specific brand of scratch tester was removed from Appendix X1 editorially in September 2009.

1. Scope

1.1 This test method covers laboratory procedures for determining the scratch hardness of the surfaces of solid materials. Within certain limitations, as described in this guide, this test method is applicable to metals, ceramics, polymers, and coated surfaces. The scratch hardness test, as described herein, is not intended to be used as a means to determine coating adhesion, nor is it intended for use with other than specific hemispherically-tipped, conical styli.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard may involve hazardous materials, operations, and equipment. 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]
G40 Terminology Relating to Wear and Erosion
G117 Guide for Calculating and Reporting Measures of Precision Using Data from Interlaboratory Wear or Erosion Tests

3. Terminology

3.1 *Definitions*—For definitions of terms applicable to this standard see Terminology G40.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *scratch hardness number, n*—a quantity, expressed in units of force per unit area, that characterizes the resistance of a solid surface to penetration by a moving stylus of given tip radius under a constant normal force and speed; namely,

$$HS_P = \frac{k\,P}{w^2}$$

where:

HS_P = scratch hardness number,
k = a geometrical constant,
P = applied normal force, and
w = scratch width.

NOTE 1—The constant k may be chosen to include conversion factors for expressing HS_P in units of GPa. For HS_P in GPa, P in grams-force, and w in µm, k = 24.98.

3.2.2 *scratching force, n*—the force that opposes relative motion between a moving stylus and the surface that is being scratched by that stylus, and which is perpendicular to the normal force exerted by the stylus.

3.2.3 *stylus drag coefficient, n—in scratch testing*, the dimensionless ratio of the scratching force to the normal force applied to the stylus; namely,

$$D_{sc} = \frac{F_{scr}}{P}$$

where:

D_{sc} = stylus drag coefficient,
F_{scr} = scratching force, and
P = normal force.

4. Summary of Test Method

4.1 This test involves producing a scratch in a solid surface by moving a diamond stylus of specified geometry along a specified path under a constant normal force and with a constant speed. The average width of the scratch is measured, and that value is used to compute the scratch hardness number in units of pressure.

4.2 As an option, the scratching force may be measured during this test and used to compute a stylus drag coefficient, which is a dimensionless measure of the resistance of the test surface to deformation by a tangentially-moving stylus.

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[1] This test method is under the jurisdiction of ASTM Committee G02 on Wear and Erosion and is the direct responsibility of Subcommittee G02.30 on Abrasive Wear.

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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.

4.3 This test is usually conducted under unlubricated conditions and at room temperature; however, it is possible to conduct scratch hardness tests under lubricated and elevated temperature conditions. The provisions of this standard allow testing under both conditions provided that requirements for valid scratch hardness testing are met and that the testing conditions are fully reported.

4.4 Effects of moisture in the air and other ambient atmospheric conditions may affect results depending on the sensitivity of the test material to the environment. If such effects are either expected or observed during the course of testing, precautions to control the surrounding atmosphere and to document the relative humidity level should be taken and reported.

5. Significance and Use

5.1 This test method is intended to measure the resistance of solid surfaces to permanent deformation under the action of a single point (stylus tip). It is a companion method to quasi-static hardness tests in which a stylus is pressed into a surface under a certain normal load and the resultant depth or impression size is used to compute a hardness number. Scratch hardness numbers, unlike quasi-static hardness numbers, involve a different combination of properties of the surface because the indenter, in this case a diamond stylus, moves tangentially along the surface. Therefore, the stress state under the scratching stylus differs from that produced under a quasi-static indenter. Scratch hardness numbers are in principle a more appropriate measure of the damage resistance of a material to surface damage processes like two-body abrasion than are quasi-static hardness numbers.

5.2 This test method is applicable to a wide range of materials. These include metals, alloys, and some polymers. The main criteria are that the scratching process produces a measurable scratch in the surface being tested without causing catastrophic fracture, spallation, or extensive delamination of surface material. Severe damage to the test surface, such that the scratch width is not clearly identifiable or that the edges of the scratch are chipped or distorted, invalidates the use of this test method to determine a scratch hardness number. Since the degree and type of surface damage in a material may vary with applied load, the applicability of this test to certain classes of materials may be limited by the maximum load at which valid scratch width measurements can be made.

5.3 The resistance of a material to abrasion by a single point may be affected by its sensitivity to the strain rate of the deformation process. Therefore, this test is conducted under low stylus traversing speeds. Use of a slow scratching speed also minimizes the possible effects of frictional heating.

5.4 This test uses measurements of the residual scratch width after the stylus has been removed to compute the scratch hardness number. Therefore, it reflects the permanent deformation resulting from scratching and not the instantaneous state of combined elastic and plastic deformation of the surface.

6. Apparatus

6.1 *General Description*—The apparatus consists of (*1*) the rigid stylus mount and specimen holding fixture, (*2*) a means to apply a normal force while traversing the stylus along the surface at constant speed, and (*3*) a means to measure the width of the scratch. Optionally, the apparatus can be equipped with a sensor to detect the magnitude of the scratching force.

6.1.1 *Stylus*—The stylus shall be conical of apex angle 120 ± 5°, and the cone shall terminate in a hemispherical tip of 200 µm (± 10 µm) radius. The material of the tip shall be diamond.

NOTE 2—The smaller the tip radius, the higher the contact stress under a given normal force. If a tip radius other than that indicated here is used, results shall indicate that a modified version of the standard was used, and the size of the tip radius shall be reported (see also 10.1.1).

6.1.2 *Apparatus*—A means to traverse the specimen under the stylus, or the stylus across the specimen, under constant speed and normal force, shall be provided. Fixtures shall be sufficiently rigid to withstand the normal, lateral, and tangential forces associated with the scratching process without undue elastic or plastic deflection. The path of the stylus may be in a straight line or an arc, as produced using a rotating table-type device.

6.1.3 *Scratch Width Measurement System*—A means for measuring the width of the scratch shall be provided. This can consist of any imaging system that is capable of magnifying the scratch such that its width can be accurately determined. The measuring system shall be capable of measuring the width of the scratch to a precision of at least 2 %. For example, the required resolution for a measuring optical microscope needed for an average 50 µm-wide scratch shall be (0.02 × 50 µm) = 1.0 µm or better. Reflecting-type, optical microscopes using monochromatic illumination or interference-contrast and having a measuring eyepiece are suitable for scratch measurement. Alternatively, photographic or video images may be used as long as the magnifications are properly calibrated.

6.1.4 *Scratching Force (Optional)*—A load cell or similar force-sensing device can be used to measure the scratching forces generated during sliding. This standard does not specify a method for measuring the scratching force, only that the sensor shall be capable of being calibrated in the direction of the scratching force and in line with the contact point between the stylus and surface.

7. Calibration

7.1 The parts of the apparatus that require calibration are (*1*) the normal force application system, (*2*) stylus traverse speed, and optionally (*3*) the scratching force sensor.

7.2 *Loading System*—The normal force applied to the stylus while it is traversing the surface shall be calibrated in such a way that the normal force is known to within 1 %. For example, a normal force of 1 N shall be applied to within an accuracy of ± 0.01 N. The means to calibrate the scratch tester shall be determined by its individual design; however, the method of normal force calibration shall be stated in the report.

NOTE 3—One method to calibrate the normal force on the stylus is to use a quasi-static system such as a button-type load cell placed under the stylus tip in the position where the test specimen is located.

7.3 *Stylus Traverse Speed*—The speed of the stylus across the surface s may be calibrated in any suitable manner such as timing the period t required to produce a scratch of length L. Thus:

$$s = \frac{L}{t} \tag{1}$$

7.4 *Scratching Force Sensor (Optional)*—The scratching force sensor shall be calibrated periodically in the direction of the scratching force, and as closely as possible in line with the point of contact between the stylus and specimen. The interval between calibrations shall be determined by the user to ensure accurate readings of scratching force and compensate for any electronic signal drift.

8. Procedure

8.1 *Specimen Preparation*—The test specimen shall be prepared in such a way as to represent the application of interest or polished to facilitate observation and measurement of scratch width. A surface may be unsuitable for scratch testing if its roughness or porosity is such that the edges of the scratch are indistinct or jagged, or if the stylus cannot traverse the surface without skipping along it or catching in a pocket. In a polished condition, the surface should be as free as possible from preparation artifacts such as grinding-induced cracks, gross grinding marks, and grain pull-out. Surface roughnesses of 0.02 to 0.05 µm R_a (arithmetic average roughness) are typical of polished surfaces. Surfaces may be scratch tested in the as-fabricated condition as long as the characteristics of the scratch do not display the types of artifacts described in this paragraph.

8.2 *Specimen Cleaning*—Since many different kinds of materials can be scratch tested, one specific cleaning treatment cannot be given. Specimens shall be cleaned in such a way that the surface is free from grit, grease, fingerprints, or other contaminants. Metals and alloys may be cleaned in non-polar solvents. Plastics may require alternative cleaning with eyeglass cleaner or similar. If contact with solvents or cleaners could result in changes to their properties, surfaces may be tested as-received. The method of cleaning, if any, shall be described in the report.

8.3 *Inspection of the Stylus*—Inspect the stylus tip with a microscope or other topographic inspection method to ensure that there are no defects (cracks, chips), wear or adhering material left from manufacturing or resulting from a previous test. Wiping the stylus with a soft cloth moistened with acetone or other cleaning solvent is usually suitable.

NOTE 4—Oily residues on the stylus can lubricate the surface, reduce the scratch width, and increase the apparent scratch hardness number. Chipped styli can increase the scratching force and produce striae that extend along the entire bottom of the scratch.

8.4 *Normal Force*—The normal force shall be selected so as to produce a measurable groove in the surface, but it shall not be so large as to cause fracture, spalling, delamination, or other form of gross surface damage. A series of scratches at different normal forces may be used to assess the resistance of the test material to increasing localized stresses.

8.5 *Stroke Length and Shape*—The stroke length shall be at least 5 mm. Strokes need not be linear, but may be in the shape of an arc, as in the case of turntable-type scratching apparatus.

8.6 *Scratching Speed*—The scratching speed shall be constant along the measured portion of the scratch, and in the range of 0.2 to 5.0 mm s^{-1}.

8.7 *Conducting the Test*—Ensure that the instrument is leveled and that the stylus is normal to the test surface while scratching. Lower the stylus to apply the load on the specimen surface gently to avoid impact damage. Activate the traversing drive to produce the scratch of desired length. Raise the stylus off of the surface. Select another location at least 5 scratch widths away from the previous scratch and produce another scratch parallel to the first. Repeat as necessary, but with a minimum of three (3) scratches per value of the normal force. Measure the scratch width as described in 8.8.

8.8 *Scratch Width Measurement*—Using a measuring microscope or other calibrated magnifying or surface profiling system, measure the width of each scratch at three locations spaced approximately equally along the length of the scratch. The width of the scratch shall be determined optically, as shown by the examples in Fig. 1. Owing to acceleration and deceleration effects, scratch widths should not be measured near the ends of the scratch.

NOTE 5—Other methods, such as surface profiling, may produce values different from optical measurements. Therefore, to improve consistency, widths should be measured on enlarged images.

8.8.1 *Special Considerations in Optical Scratch Measurement*—The characteristics of the surfaces being tested, such as their roughness, color, degree of light diffusion, extent of plastic deformation, and reflectivity, will all affect the ease or difficulty in precisely locating scratch edges. In general, finer scratches present more difficulties in width measurement than wider scratches (see also 11.2). It may be necessary to use special lighting methods, such as oblique illumination, polarized light, or differential inference contrast microscopy to provide sufficient contrast to measure the scratch widths optically. Report the use of special lighting methods, when applicable.

9. Calculations

9.1 *Scratch Hardness Number*—The scratch hardness number is calculated by dividing the applied normal force on the stylus by the projected area of scratching contact, assuming that the hemispherically-tipped stylus produces a groove whose leading surface has a radius of curvature r, the tip radius of the stylus. The projected area of the contact surface is therefore a semi-circle whose diameter is the final scratch width, as shown in Fig. 2. Therefore,

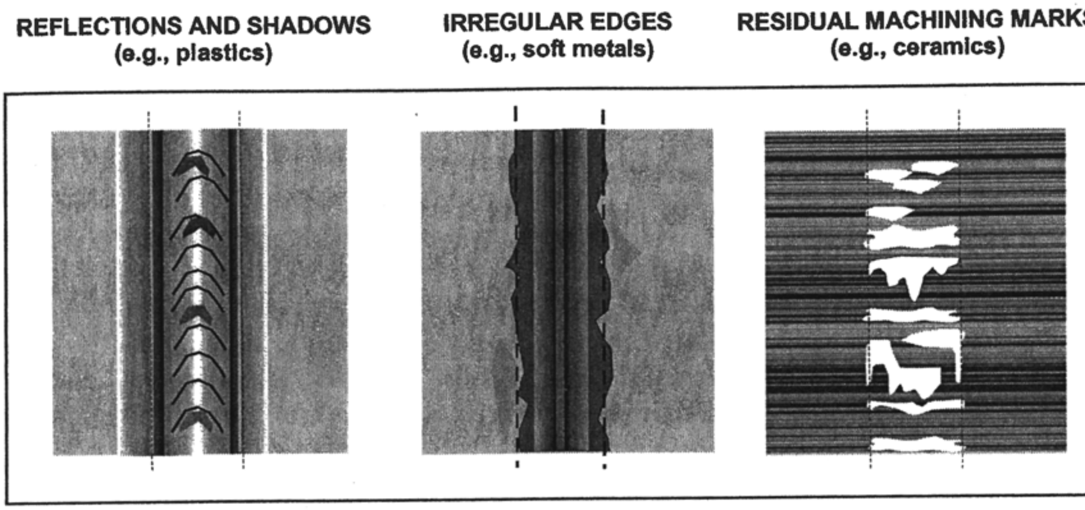
$$HS_P = \frac{8P}{\pi w^2} \tag{2}$$

where:

HS_P = scratch hardness number, Pa,
P = normal force, N, and
w = scratch width, m.

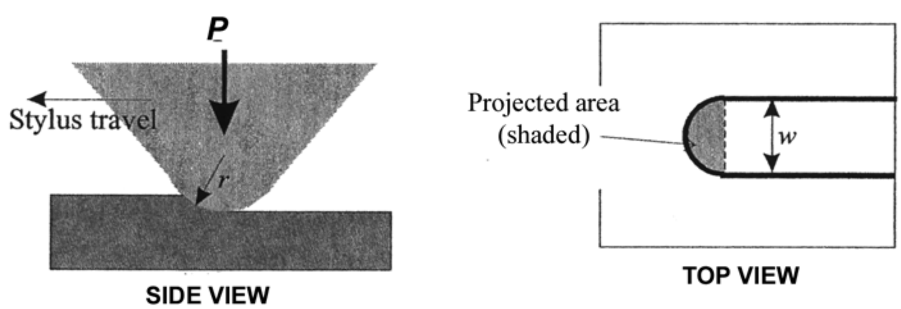
If the normal force on the stylus is applied by means of a dead-weight of m grams directly above it, and the scratch width x is in units of µm, then Eq 2, which provides the scratch hardness number in GPa, becomes:

$$HS_P = 24.98 \frac{m}{x^2} \tag{3}$$



NOTE 1—The microscope fine focus control can be used to identify the edges of a track displaying reflections and shadows (left). The width of scratches in a poly-grained metal can be estimated by placing the cursor lines through the apparent centers of the rough edges (center). Scratches on machined surfaces or hard materials may be discontinuous. Such artifacts cannot be used to obtain a valid scratch hardness number (right).

FIG. 1 Illustration of Identifying the Widths of Scratches in Different Kinds of Materials



NOTE 1—The contact of the stylus is assumed to produce a semi-circular projected area when viewed from the top.

FIG. 2 Final Scratch Width

Since the state of stress at the stylus tip is a function of contact geometry and applied force, the magnitude of the scratch hardness number is dependent upon both the stylus tip radius and the normal load. Since the tip radius prescribed in this standard is established, it need not be reported separately; however, P should be reported with HS_P.

NOTE 6—At certain critical values of contact stress, the deformation and fracture behavior of certain materials may undergo a transition, leading to a change in both the morphology of the scratch and the scratch hardness number. For example, the HS_P for bulk polymethylmethacrylate and for polyamine coatings on steel have been observed to exhibit a decrease with increasing normal force. Thus, it is important to compare HS_P for different materials only under the same normal forces and tip radius.

9.2 *Stylus Drag Coefficient*—The stylus drag coefficient (D_{sc}) is the dimensionless ratio of the scratching force to the normal force, calculated as follows:

$$D_{sc} = \frac{F_{scr}}{P} \tag{4}$$

where:

D_{sc} = stylus drag coefficient,
F_{scr} = average scratching force along the length of the scratch, N, and
P = normal force on the stylus, N.

NOTE 7—D_{sc} is similar in definition to, but not the same as, the kinetic friction coefficient. D_{sc} specifically refers to the resistance offered by the test surface to the displacement of material ahead of a traversing, hard stylus of controlled shape. Therefore, it is not in general equal to the friction coefficient for diamond, the typical stylus material, sliding against the test specimen material.

10. Report

10.1 Report the following:

10.1.1 *Characterization of the Stylus*—Report the tip radius in µm if other than 200 ± 10 µm. If other than 200 ± 10 µm, the report shall indicate that the scratch hardness numbers were obtained under non-standard conditions, and results should not be compared with those obtained using a 200 ± 10 µm stylus tip radius.

10.1.2 *Test Specimens*—Provide information sufficient to establish the source, chemical composition, processing history, surface treatment, and surface roughness of the test specimen surface. Commercial designations for materials should be given, if applicable. In the case of coated surfaces, indicate the thickness of the coating.

10.1.3 *Test Conditions and Method of Measurement*—Report the normal force(s) used (N), scratching speed (mm s^{-1}), and stroke length (mm). Also describe the type of scratch tester used, including any commercial model numbers, and the method used to measure the scratch width.

10.1.4 *Scratch Hardness Number*—Report the average scratch hardness number, in GPa , obtained from a minimum of three scratches per specimen. Thus, a total of nine determinations shall be made for each specimen surface at each selected normal force (that is, 3 scratches times 3 width measurement locations per scratch).

10.1.5 *Reporting Optional*—Report the average stylus drag coefficient, as obtained from measurements of the average scratching force on each test. Indicate the means used to measure and calculate the average scratching force.

10.1.6 *Observations*—Report the presence of any cracks or other defects associated with the scratches.

NOTE 8—As the normal force on the stylus is increased on many materials, there is an increasing tendency for the formation of microfractures, chips, and other forms of surface damage. It is sometimes helpful to report the occurrence of such features. If the extent of damage is significant, such as the production of large surface chips or spalls, then the scratch hardness number, even when obtained from unspalled portions of the track should not be considered valid.

11. Precision and Bias[3]

11.1 *Precision*—The precision of scratch hardness determinations is dependent on the scratching characteristics of the given material or coating. Scratches on some materials have relatively easy-to-detect, straight edges. In other cases, more judgment is required to identify the edges of the scratch. Since this measurement is dependent on the morphology of scratch edge features, it is not possible to state in absolute terms the precision for this test method. Note also that any uncertainty embodied within the scratch width measurement is doubled in the computation of the scratch hardness number.

11.2 *Repeatability and Reproducibility*—The repeatability of scratch hardness testing results is dependent on the magnitude of the normal force, the accuracy of the width measuring system, the deformational characteristics of the materials being scratched, and operator as to the location of the scratch edges. The lower the normal force, the narrower the scratch width, and therefore, the larger the effects of measurement errors on the repeatability of scratch hardness numbers. The optical readability (for example, contrast) of scratch edges and the nature of scratching-induced damage to the test surface will affect the repeatability of the results. For example, a microscope measuring system may be capable of measuring to 0.5 µm or better, but the scratch could have a wavy edge variability five times greater than that. If profiling instruments are used to measure width, the point at which this stylus enters and leaves a wavy-edged track will affect the width measurement as well. Therefore, neither stylus profiling nor optical microscopy measurement is inherently immune from the effects of material deformation artifacts on repeatability. Appendix X1 provides examples of the repeatability and reproducibility of optical microscope-based scratch width measurements on a polished metal and a polymer specimen. The general reproducibility of this test method has not been established.

11.3 *Bias*—Since there is no accepted reference material for determining the bias of the procedures in scratch hardness testing, there is no basis upon which to determine the bias.

12. Discussion

12.1 Scratch hardness tests are one of many micromechanical tests used to characterize the surfaces of materials. The values of the scratch hardness number, as defined herein, can be affected by a variety of factors including stylus shape, stylus dimensions, applied normal force, scratching speed, surface cleanliness, and uniformity of the material being tested. Like other types of hardness numbers, it does not measure a single fundamental materials property, but instead reflects the conjoint influences of a number of material properties responding to the loading conditions and penetration geometry imposed by the test. Therefore, one should not attempt to compare the scratch hardness numbers for various materials of interest unless the testing conditions are the same.

12.2 *Penetration Geometry*—Since the stylus tip geometry used here is a rounded-end cone, at a certain penetration depth, the sliding geometry changes. The depth at which a rounded tip blends into the conical portion of the stylus can be called the geometric transition depth (z_{gt}) and may be calculated from the tip radius r and the tip apex angle α (degrees) as follows:

$$z_{gt} = r(1 - \cos \theta_{deg}) \quad (5)$$

where:

$$\theta_{deg} = \frac{1}{2}(180 - \alpha_{deg}) \quad (6)$$

A tip of radius 200 µm and apex angle of 120° gives z_{gt} = 26.8 µm. By comparison, a tip radius of 210 µm and with an apex angle of 123° gives z_{gt} = 25.4 µm.

NOTE 9—There are no known data that indicate significant effects on scratch hardness numbers from exceeding the geometric transition depth. However, when interpreting scratch hardness results having a range of scratch depths, and when observing of scratch-induced damage, one should consider the possible effects of the sphere-to-cone transition on stress distribution and material flow characteristics.

12.3 Correlations of scratch hardness numbers with other material characteristics, such as abrasive wear resistance, will depend on the extent to which the response of the surface in use is controlled by the same combination of properties which determine the scratch hardness number for that material. Therefore the user of this standard should establish his or her own correlations between scratch hardness numbers and wear characteristics of interest.

12.4 Use of scratch hardness numbers in fundamental studies of material deformation may require the measurement of additional quantities associated with the morphology of the scratch grooves, and an alternative method for computing the resistance of a surface to single-point abrasion may be needed.

[3] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR: RR:G02-1012.

13. Keywords

13.1 scratch; scratch hardness; single-point abrasion; stylus

APPENDIX

(Nonmandatory Information)

X1. INTERLABORATORY TESTS ON THE REPEATABILITY AND REPRODUCIBILITY OF SCRATCH WIDTH MEASUREMENTS[3]

X1.1 Purpose

X1.1.1 This interlaboratory testing project was designed to determine the typical variability to be expected in scratch width measurements on two materials of varying resistance to scratching; namely, polymethylmethacrylate (PMMA) and brass (70 Cu-30 Zn).

X1.2 Procedure

X1.2.1 Three parallel scratches were placed on specimens of both PMMA (as-received) and metallographically polished brass using a 200 gf (1.96 N) load and a 200 µm-radius diamond stylus. A constant load, linear, commercially-made scratch-testing apparatus was used. In addition to the scratches, a series of Vickers microindentations were also placed on the two test specimens. The square shapes of the microindentations provided the means to compare laboratory optical measurements using less judgment than is involved with scratch widths. The pattern of microindentations and scratches is shown in Fig. X1.1. Five participants were asked to measure the width of each scratch at the points labelled "S_," and the length of the Vickers diagonals at the points labelled "V_." A total of 9 width measurements and 6 diagonal length measurements was made on each specimen. The same specimens were circulated to all participating laboratories.

X1.3 Results

X1.3.1 Data from the five participating laboratories were reduced using Guide G117. Table X1.1 summarizes the scratch width measurement results. Coefficients of variation are given in Table X1.2.

X1.4 Scratch Hardness Numbers

X1.4.1 The average scratch widths from the participating laboratories were converted to average scratch hardness numbers using Eq 3. The between-laboratory standard deviation was used to calculate the errors. These quantities were: $HS_{1.96N}$ = 1.13 (± 0.08) GPa for brass, and $HS_{1.96N}$ = 0.123 (± 0.01) GPa for PMMA.

NOTE X1.1—Since the scratch width is squared in calculating HSP, any errors in width measurement are multiplied in the calculated scratch hardness number.

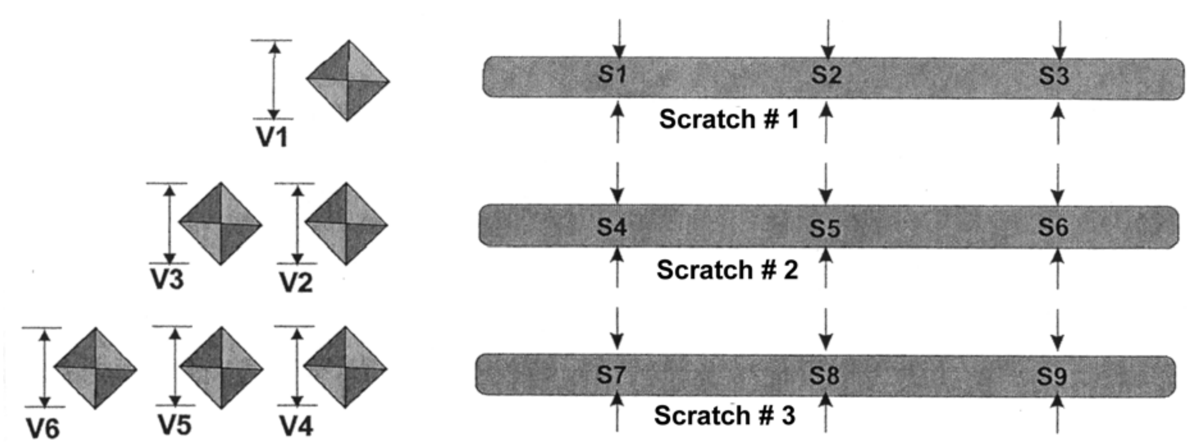


FIG. X1.1 Pattern of Scratches and Vickers Micro-indentations on Test Coupons

TABLE X1.1 Summary of Interlaboratory Measurements of Scratch Widths on the Same Two Specimens of PMMA and Brass

NOTE 1—Each laboratory made 9 replicate measurements.

Specimen	Lab	Average Scratch Width (µm)	Within-Lab Std. Dev. (µm)	Between Lab Dev. from Average (µm)
Brass	A	66.0	0.44	-0.56
	B	68.7	1.90	2.14
	C	68.0	1.48	1.44
	D	63.2	1.21	-3.36
	E	66.9	2.42	0.34
	Average	66.6	1.63	2.64
PMMA	A	203.2	0.00	1.28
	B	204.8	2.13	2.88
	C	205.3	0.81	3.38
	D	194.4	0.75	-7.53
	E	[A]	[A]	[A]
	Average[B]	201.9	1.20	5.22

[A] The data for Lab E failed the test for statistical outliers, per Guide G117. It is suspected that an incorrect magnification factor was used to calculate scratch widths since the values were consistently about ½ the typical values for PMMA as measured by the other four laboratories.
[B] Not including Lab E.

TABLE X1.2 Coefficients of Variation and 95 % Confidence Limits for Scratch Widths on the Same Two Specimens of PMMA and Brass

Material	Within-Lab C.O.V.(%)	Repeatability 95 % Limit	Between-Lab C.O.V. (%)	Reproducibility 95 % Limit
Brass	2.5	4.57	4.0	7.39
PMMA	0.6	3.36	2.6	14.62