INTERNATIONAL

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Standard Test Method for Magnetic Properties of High-Coercivity Permanent Magnet Materials Using Hysteresigraphs[1]

This standard is issued under the fixed designation A 977/A 977M; 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~~covers how to determine the magnetic characteristics of magnetically hard materials (permanent magnets), particularly their initial magnetization, demagnetization, and recoil curves, and such quantities as the residual induction, coercive field strength, knee field, energy ~~products,~~product, and recoil permeability. This test method is suitable for all materials processed into bulk magnets by any common fabrication technique (casting, sintering, rolling, molding, and so forth), but not for thin films or for magnets that are very small or of unusual shape. Uniformity of composition, structure, and properties throughout the magnet volume is necessary to obtain repeatable results. Particular attention is paid to the problems posed by modern materials combining very high coercivity with high saturation induction, such as the rare-earth magnets, for which older test methods (see Test Method A 341) are unsuitable. An applicable international standard is IEC Publication 60404-5.

1.2 The magnetic system (circuit) in a device or machine generally comprises flux-conducting and nonmagnetic structural members with air gaps in addition to the permanent magnet. The system behavior depends on properties and geometry of all these components and on the operating temperature. ~~The tests described here measure~~ This test method describes only how to measure the properties of the permanent magnet material. The basic test method incorporates the magnetic specimen in a magnetic circuit with a closed flux path. Test methods using ring samples or frames composed entirely of the magnetic material to be characterized, as commonly used for magnetically soft materials, are not applicable to permanent magnets.

1.3 This test method shall be used in conjunction with Practice A 34/A 34M.

1.4 The values and equations stated in customary (cgs-emu or inch-pound) or SI units are to be regarded separately as standard. Within this test method, SI units are shown in brackets except for the sections concerning calculations where there are separate sections for the respective unit systems. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in nonconformance with this test method.

1.5 The names and symbols of magnetic quantities used in this test method, summarized in Table 1, are those ~~currently preferred~~generally accepted by ~~U.S.~~the industry.

1.6 This test method is useful for magnet materials having H_{ci} values between about 100 Oe and 35 kOe [8 kA/m and 2.8 MA/m], and B_r values in the approximate range from 500 G to 20 kG [50 mT to 2 T]. High-coercivity rare-earth magnet test specimens may require much higher magnetizing fields than iron-core electromagnets can produce. Such samples must be premagnetized externally and transferred into the measuring yoke. Typical values of the magnetizing fields, H_{mag}, required for saturating magnet materials are shown in Table A2.1.

1.7 *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]

A 34/A 34M Practice for ~~Procurement Testing~~ Sampling and ~~Sampling~~ Procurement Testing of Magnetic Materials

A 340 Terminology of Symbols and Definitions Relating to Magnetic Testing

A 341/A 341M Test Method for Direct Current Magnetic Properties of Materials Using ~~dc~~D-C Permeameters and the Ballistic Test Methods

E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

[1] This test method is under the jurisdiction of ASTM Committee A06 on Magnetic Properties and is the direct responsibility of Subcommittee A06.01 on Test Methods.
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Current edition approved Nov. 1, 2007. Published December 2007. Originally approved in 1997. Last previous edition approved in 2002 as A 977/A 977M–02.

[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* ~~, Vol 03.04.~~volume information, refer to the standard's Document Summary page on the ASTM website.

TABLE 1 Symbols, Quantities, and Units

NOTE 1—IEC nomenclature calls B_r "remanence," when B_r represents the B at $H = 0$ of the outermost hysteresis loop, and it calls B_r "remanent magnetic induction" for B at $H = 0$ at smaller loops.

Symbol	Quantity	SI Unit	Customary cgs-emu
A_t	Cross section of search coil	[m^2]	cm^2
B_d	Magnetic induction at BH_{max}	[T]	G
B_{rec}	Magnetic induction at low point of recoil loop	[T]	G
B_r	Magnetic induction at remanence	[T]	G
d_l	Diameter of pole piece	[m]	cm
d_2	Diameter of homogeneous field	[m]	cm
H_d	Magnetic field strength at BH_{max}	[A/m]	Oe
H_p	Magnetic field strength at low point of recoil loop	[A/m]	Oe
l	Distance between pole faces	[m]	cm
l_r	Length of test sample	[m]	cm
N	Number of turns of test coil		
e	Voltage induced in test coil	V	V
d	Total air gap between test sample and pole faces	[m]	cm
μ_0	A constant with value $\mu_0 = 4\pi\ 10^{-7}$ H/m		
μ_{rec}	Recoil permability		

2.2 *Magnetic Materials Procedure Association Standard:*[3]

MMPA No. 0100–96 Standard Specifications for Permanent Magnet Materials

[3] Annual Book of ASTM Standards, Vol 14.02.
[3] Available from Magnetic Materials Producers Association, 8 S. Michigan Ave., Suite 1000, Chicago, IL 60603.

~~2.3 *International Electrotechnical Commission Document:*~~ *MMPA No. 0100–00 Standard Specifications for Permanent Magnet Materials*

2.3 *International Electrotechnical Commission Document:*[4]

Publication ~~404-5 Magnetic Materials~~60404-5 Magnetic Materials– Part 5: Permanent Magnet (Magnetically Hard) Materials – Methods of Measurement of Magnetic Properties

3. Terminology

3.1 Basic magnetic units are defined in Terminology A 340 and MMPA ~~Standard~~ No. ~~0100–96~~0100–00. Additional definitions with symbols and units are given in Table 1 and Figs. 1-3 of this test method.

4. Significance and Use

4.1 This test method is suitable for magnet specification, acceptance, service evaluation, quality control in magnet production, research and development, and design.

4.2 When a test specimen is cut or fabricated from a larger magnet, the magnetic properties measured on it are not necessarily exactly those of the original sample, even if the material is in the same condition. In such instances, the test results must be viewed in context of part performance history.

4.3 Tests performed in general conformity to this test method and even on the same specimen, but using different test systems, may not yield identical results. The main source of discrepancies are variations between the different test systems in the geometry of the region surrounding the sample, such as, size and shape of the electromagnet pole caps (see Annex A1 and Appendix X1), air gaps at the specimen end faces, and especially the size and location of the measuring devices for H and B or for their corresponding flux values (Hall-effect probes, inductive sensing coils). Also important is the method of B calibration, for example, a volt-second calibration of the fluxmeter alone versus an overall system calibration using a physical reference sample. The method of B and H sensing should be indicated in test reports (see Section 9).

5. Measuring Methods and Apparatus

5.1 *Measuring Flux and Induction (Flux Density)*:

5.1.1 In the preferred B-measuring method, the total flux is measured with a sensing coil (search coil) that surrounds the test specimen and is wound as closely as possible to the specimen surface. Its winding length should be no more than a third of the specimen length, preferably less than one fifth, and must be centered on the specimen. The leads shall be twisted tightly. As the flux changes in response to sweeping the applied field, H, the total flux is measured by taking the time integral of the voltage induced in this coil. This measurement is taken with a fluxmeter. Modern hysteresigraphs use electronic integrating fluxmeters that allow convenient continuous integration and direct graphic recording of magnetization curves. If the signal is large enough, high-speed voltage sampling at the coil and digital integration is also possible.

~~5.1.2The magnetic induction,~~

5.1.2 The magnetic induction B ~~,~~ is determined by dividing the total flux by the area-turns ~~product,~~product NA ~~, of the~~ *of the B-sensing coil. For permanent magnets in general, and especially for high-coercivity materials, an air-flux correction is required (see ~~5.3 and 5.4~~5.1.5).*

5.1.3 The total error of measuring B shall be not greater than ± 2 %.

5.1.4 The change of magnetic induction, $\Delta B = B_2 - B_1$, in the time interval between the times t_1 and t_2 is given as follows:

$$\Delta B = (10^8/AN) \int_{t_1}^{t_2} e\, dt \text{ (customary units)} \quad (1)$$

$$\Delta B = (1/AN) \int_{t_1}^{t_2} e\, dt \text{ (SI units)} \quad (2)$$

where:

B	=	magnetic induction, G [T];
A	=	cross-sectional area of the test specimen, cm^2 [m^2];
N	=	number of turns on the B-sensing coil;
e	=	voltage induced in the coil, V;
t	=	time, s; and
$\int_{t_1}^{t_2} e\, dt$	=	voltage integral = flux, V-s [Weber].

5.1.5 The change in the magnetic induction shall be corrected to take into account the air flux outside the test specimen that is linked by the sensing coil. The corrected change, B_{corr}, is given as follows:

$$\Delta B_{corr} = (10^8/AN) \int_{t_1}^{t_2} e\, dt - \Delta H\,(A_t - A)/A \text{ (customary units)} \quad (3)$$

~~[4] Available from Magnetic Materials Producers Association, 8 S. Michigan Ave., Suite 1000, Chicago, IL 60603.~~

[4] Available from International Electrotechnical Commission (IEC), 3 rue de Varembé, P.O. Box 131, CH-1211, Geneva 20, Switzerland.

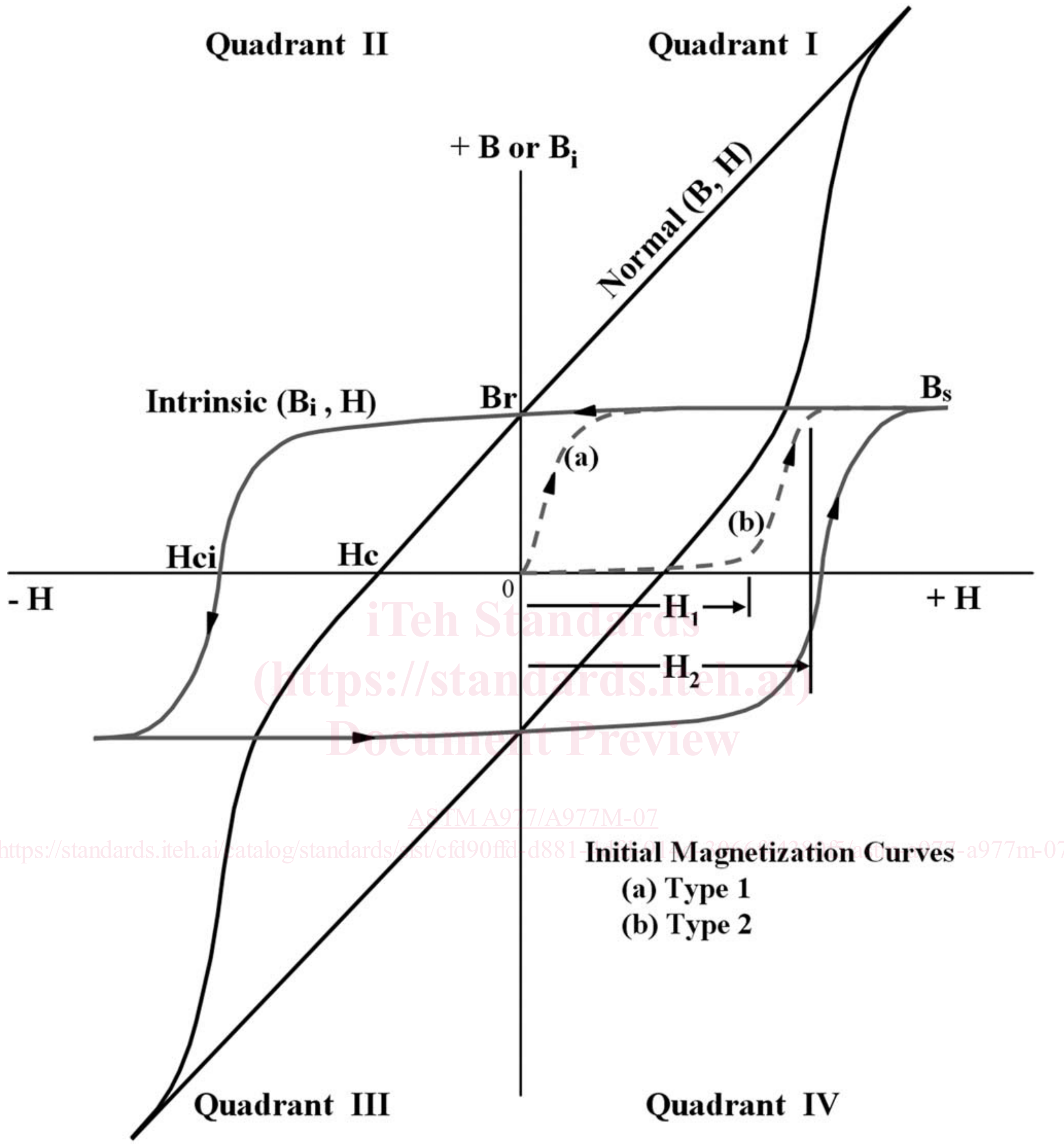

FIG. 1 Normal and Intrinsic Hysteresis Loops and Initial Magnetization Curves for Permanent Magnet Materials Illustrating Two Extremes of Virgin Sample Behavior

$$\Delta B_{corr} = (1/AN) \int_{t_1}^{t_2} e\, dt - \mu_0 \, \Delta H \; (A_t - A)/A \text{ (SI units)} \quad (4)$$

where:

A = average cross-sectional area of the sensing coil, cm^2 [m^2];
ΔH = change in field from t_1 until t_2, Oe [A/m]; and
μ_0 = magnetic constant [$4\pi \; 10^{-7}$ H/m].

5.2 *Determining Intrinsic Induction* :

5.2.1 For high-coercivity magnets, it is more convenient to sense directly an electrical signal proportional to the intrinsic induction, derive the average B_i by dividing this flux by the area-turns product of the surrounding B coil, and to plot B_i versus H~~as~~

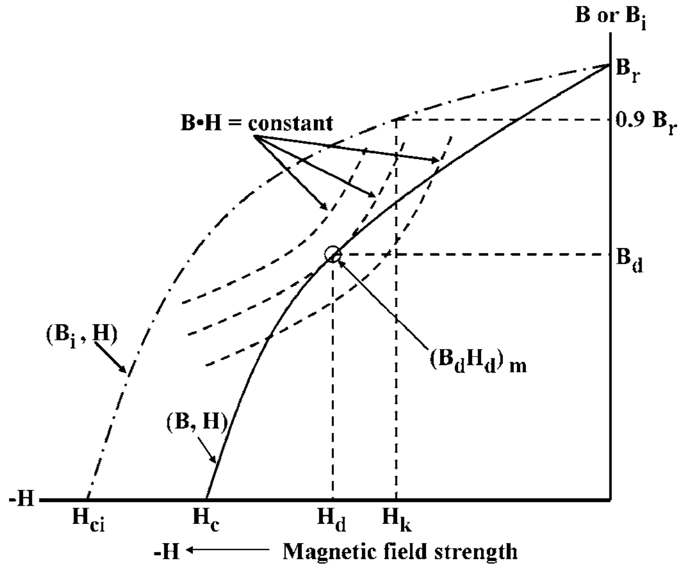

FIG. 2 Normal and Intrinsic Demagnetization Curves with Symbols for Special Points of Interest and Definition of Salient Properties. Illustration of Maximum Energy Product, Coercive Fields, and Definition of Knee Field

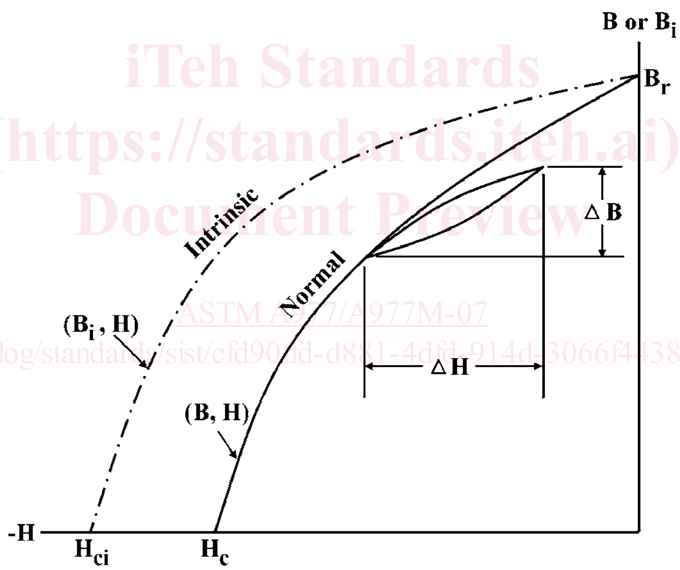

FIG. 3 Normal and Intrinsic Demagnetization Curves with Symbols for Special Points of Interest and Definition of Salient Properties. Illustration of Recoil Loop. Recoil Permeability is Defined as $\mu_{rec} = \Delta B/\Delta H$

~~the primary demagnetization curve.~~ . *B then is obtained by mathematical or electronic addition of H to B.*

5.2.2 The change of intrinsic induction in the test specimen can be determined by integrating the voltage induced in a device comprising two sensing coils, both subject to the same applied field *H*, where the test specimen is contained in only one of the coils (Coil 1). If each individual coil has the same area-turns product, and if the windings are connected electrically in opposition, the signal induced by the flux linking Coil 2 (not containing the specimen) will compensate for the output of Coil 1 except for B_i within the test specimen. The change of intrinsic induction in the specimen then is given as follows:

$$\Delta B_i = (10^8/AN) \int_{t_1}^{t_2} e\, dt \text{ (customary units)} \quad (5)$$

$$\Delta B_i = (1/AN) \int_{t_1}^{t_2} e\, dt \text{ (SI units)} \quad (6)$$

where:

B_i = intrinsic induction, G [T];
A = cross section of the test specimen, cm^2 [m^2]; and
N = number of turns on Coil 1 containing the test specimen.

5.2.3 The two-sensing-coil device shall lie totally within the homogeneous field defined by Eq A1.1 and Eq A1.2. Test specimens of lower-coercivity magnets having a range of cross-sectional areas and shapes can then be measured with the same coil device. An arrangement of side-by-side coils of equal size is useful. Serious errors, however, are incurred when measuring B_i this way on high-B_r or high/coercivity magnets, or both, at applied fields of about 10 kOe or more. The errors are most severe for test specimens of short pole-to-pole length. Local pole-piece saturation causes strong field inhomogeneities. The specimen then must fill the cross section of Coil 1, and Coil 2 must be a thin and flat coil, or a coaxial annular coil, either centered on the specimen or in close proximity to its surface (see 5.3).

5.2.4 The total error of measuring B_i shall be not greater than ±2 %.

5.3 *Measuring the Magnetic Field Strength*:

5.3.1 For correct magnetization curves, one should know the magnetic field strength, H, inside the test specimen, averaged over the specimen volume if H is not uniform. But this inner field cannot be measured. At the surface of the test specimen, H is equal to the local field strength just inside the specimen in those locations (and only there) where the H vector is parallel to the side surface of the specimen. Therefore, a magnetic field strength sensor of small dimensions relative to the specimen is placed near the specimen surface and symmetrical with respect to the end faces, covering the shortest possible center portion of the specimen length. It shall be so oriented that it correctly measures the tangential field component.

5.3.2 To determine the magnetic field strength, a flat surface coil, a tightly fitted annular coil, a magnetic potentiometer, or a Hall probe is used together with suitable instruments. The dimensions of the magnetic field sensor and its location shall be such that it is within an area of limited diameter around the test specimen (see Annex A1).

5.3.3 The provisions of 5.3.2 are adequate for measurements on magnets having low-to-moderate intrinsic coercivity, such as Alnico and bonded ferrites. For high-coercivity, dense ferrites and especially for most rare earth-transition metal materials, it is essential for accurate measurement to use thin flat or radially thin annular H -sensing coils of short length (<1/5 to 1/3 of the specimen length), centered on the specimen and placed as close as possible to the specimen surface.

5.3.4 The same considerations apply to the H-flux compensation coil used in B_i measurements (see 5.2.3.) When pole saturation can occur, Coil 2 also shall be a thin conforming flat surface coil for rectangular specimen shapes or a thin annular coil closely surrounding a cyclindrical specimen, and the specimen essentially shall fill the open cross-sectional area of the B–sensing Coil 1.

5.3.5 To reduce other measurement errors, the air gaps between the flat ends of the test specimen and the pole pieces shall be kept small, typically in the range 0.001 to 0.002 in. [0.025 to 0.050 mm] (see Fig. 4).

5.3.6 The magnetic field strength measuring system shall be calibrated. Any temperature dependence of the measuring instruments, (for example, Hall probes), must be taken into account. The total error of measuring H shall be not greater than ±2 %.

NOTE 1—The end faces of the test specimen should be in intimate contact with the pole faces. There are always unavoidable small air gaps as a result of surface roughness, poor parallelism of sample or pole faces, or intentional shimming to protect delicate specimens from deformation or crushing. These cause additional errors in the magnetic field strength measurement and indirectly in the B_i measurements through air flux compensation errors, even in the low H region. The maximum error in the field strength measurement, as a result of two symmetric gaps of length d (see Fig. 3) is approximately:

$$\Delta H/H = 2\,B\,d\,/\,l_r\,H \text{ (customary units)} \quad (7)$$

$$\Delta H/H = 2\,B\,d\,/\,\mu_0\,l_r\,H \text{ (SI units)} \quad (8)$$

To keep the error 100 $\Delta H/H < 1$ % in the region of the $(BH)_{max}$ point, the gap thickness should be kept below the following values:

$d = 0.00025\ l_r$ for Alnico magnets,
$d = 0.005\ l_r$ for hard ferrite magnets, and
$d = 0.003\ l_r$ for rare-earth magnets.

5.4 *Plotting Magnetization and Demagnetization Curves*:

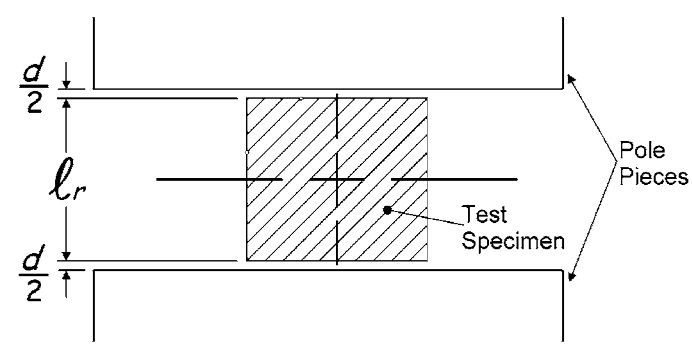

FIG. 4 Illustration Regarding the Influence of Air Gaps at the End Faces of the Test Specimen