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.

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Standard Test Methods for Determining Average Grain Size Using Semiautomatic and Automatic Image Analysis[1]

This standard is issued under the fixed designation E1382; 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.

INTRODUCTION

These test methods may be used to determine the mean grain size, or the distribution of grain intercept lengths or areas, in metallic and nonmetallic polycrystalline materials. The test methods may be applied to specimens with equiaxed or elongated grain structures with either uniform or duplex grain size distributions. Either semiautomatic or automatic image analysis devices may be utilized to perform the measurements.

1. Scope

1.1 These test methods are used to determine grain size from measurements of grain intercept lengths, intercept counts, intersection counts, grain boundary length, and grain areas.

1.2 These measurements are made with a semiautomatic digitizing tablet or by automatic image analysis using an image of the grain structure produced by a microscope.

1.3 These test methods are applicable to any type of grain structure or grain size distribution as long as the grain boundaries can be clearly delineated by etching and subsequent image processing, if necessary.

1.4 These test methods are applicable to measurement of other grain-like microstructures, such as cell structures.

1.5 This standard deals only with the recommended test methods and nothing in it should be construed as defining or establishing limits of acceptability or fitness for purpose of the materials tested.

1.6 The sections appear in the following order:

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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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

[1] These test methods are under the jurisdiction of ASTM Committee E04 on Metallography and are the direct responsibility of Subcommittee E04.14 on Quantitative Metallography.

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1.8 *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:*[2]

E3 Guide for Preparation of Metallographic Specimens
E7 Terminology Relating to Metallography
E112 Test Methods for Determining Average Grain Size
E407 Practice for Microetching Metals and Alloys
E562 Test Method for Determining Volume Fraction by Systematic Manual Point Count
E883 Guide for Reflected–Light Photomicrography
E930 Test Methods for Estimating the Largest Grain Observed in a Metallographic Section (ALA Grain Size)
E1181 Test Methods for Characterizing Duplex Grain Sizes
E1245 Practice for Determining the Inclusion or Second-Phase Constituent Content of Metals by Automatic Image Analysis

3. Terminology

3.1 *Definitions*—For definitions of terms used in these test methods, (*feature-specific measurement, field measurement, flicker method, grain size, gray level,* and *threshold setting*), see Terminology E7.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *chord (intercept) length*—the distance between two opposed, adjacent grain boundary intersection points on a straight test line segment that crosses the grain at any location due to random placement of the test line.

3.2.2 *grain intercept count*—determination of the number of times a test line cuts through individual grains on the plane of polish (tangent hits are considered as one half an interception).

3.2.3 *grain boundary intersection count*—determination of the number of times a test line cuts across, or is tangent to, grain boundaries (triple point intersections are considered as 1½ intersections).

3.2.4 *image processing*—a generic term covering a variety of video techniques that are used to enhance or modify contrast, find and enhance edges, clean images, and so forth, prior to measurement.

3.2.5 *skeletonization*—an iterative image amendment procedure in which pixels are removed from the periphery of the grain boundaries ("thinning"), or other features, unless removal would produce a loss of connectivity, until each pixel has no more than two nearest neighbors (except at a junction); this is followed by extension of line ends until they meet other line ends, to connect missing or poorly delineated grain boundaries.

3.2.6 *watershed segmentation*—an iterative image amendment procedure in which each grain, or other features, is eroded to a single pixel, without loosing that pixel ("ultimate erosion"); this is followed by dilation without touching to rebuild the grain structure with a very thin line (grain boundaries) separating each grain.

3.3 *Symbols:*

α = the phase of interest for grain size measurement in a two-phase (constituent) microstructure.

$\bar{A}_\alpha$ = average area of α grains in a two-phase (constituent) microstructure.

$\bar{A}_{A\alpha}$ = area fraction of α grains in a two-phase microstructure.

A_{gi} = total area of grains in the ith field.

A_i = true area of the ith grain; or, the test area of the ith field.

$\bar{A}_i$ = mean grain area for the ith field.

A_{max} = area of the largest observed grain.

A_{ti} = true test area for the ith field.

d = diameter of test circle.

G = ASTM grain size number.

$\bar{l}$ = mean lineal intercept length.

$\bar{l}_\alpha$ = mean lineal intercept length of the α phase in a two-phase microstructure for n fields measured.

$\bar{l}_{\alpha i}$ = mean lineal intercept length of the α phase in a two-phase microstructure for the ith field.

L = test line or scan line length.

$\bar{L}_A$ = mean grain boundary length per unit test area.

L_{Ai} = grain boundary length per unit test area for the ith field.

l_i = intercept length for the ith grain.

$\bar{l}_i$ = mean intercept length for the ith field.

L_i = length of grain boundaries in the ith field.

L_{ti} = true test line or scan line length for the ith field.

L_v = length of grain edges per unit volume.

M = magnification.

n = number of fields measured or the number of grid placements (or the number of any measurements).

N = number of grains measured or the number of grain intercepts counted.

$\bar{N}_A$ = mean number of grains per unit test area for $n$fields measured.

N_{Ai} = number of grains per unit area for the ith field.

$\bar{N}_\alpha$ = mean number of α grains in a two-phase microstructure intercepted by the test lines or scan lines

$N_{\alpha i}$ = number of α grains in a two-phase microstructure intercepted by the test lines or scan lines for the ith field.

N_i = number of grains intercepted by the test lines or scan lines for the ith field; or, the number of grains counted in the ith field.

$\bar{N}_L$ = mean number of grain intercepts per unit length of test lines or scan lines for n fields measured.

N_{Li} = number of grains intercepted per unit length of test lines or scan lines for the ith field.

P_i = number of grain boundaries intersected by the test lines or scan lines for the ith field.

$\bar{P}_L$ = mean number of grain boundary intersections per unit length of test lines or scan lines for $n$fields measured.

[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.

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P_{Li} = number of grain boundary intersections per unit length of test lines or scan lines for the ith field.

$\bar{P}_{P\alpha}$ = point fraction of the α grains in a two-phase microstructure.

s_v = grain boundary surface area per unit volume.

s = standard deviation = $[(1/(n-1) \sum (X_i - \bar{X})^2]^{1/2}$.

$\bar{X}$ = any mean value = $\sum X_i / n$.

X_i = any individual measurement.

95 % CI = 95 % confidence interval.

% RA = percent relative accuracy.

4. Summary of Test Methods

4.1 Determination of the mean grain size is based on measurement of the number of grains per unit area, the length of grain boundaries in unit area, grain areas, the number of grain intercepts or grain boundary intersections per unit length, or grain intercept lengths. These measurements are made for a large number of grains, or all of the grains in a given area, within a microscopical field and then repeated on additional fields to obtain an adequate number of measurements to achieve the desired degree of statistical precision.

4.2 The distribution of grain intercept lengths or areas is accomplished by measuring intercept lengths or areas for a large number of grains and grouping the results in histogram fashion; that is, frequency of occurrence versus class limit ranges. A large number of measurements over several fields are required to obtain an adequate description of the distribution.

5. Significance and Use

5.1 These test methods cover procedures for determining the mean grain size, and the distribution of grain intercept lengths or grain areas, for polycrystalline metals and nonmetallic materials with equiaxed or deformed grain shapes, with uniform or duplex grain size distributions, and for single phase or multiphase grain structures.

5.2 The measurements are performed using semiautomatic digitizing tablet image analyzers or automatic image analyzers. These devices relieve much of the tedium associated with manual measurements, thus permitting collection of a larger amount of data and more extensive sampling which will produce better statistical definition of the grain size than by manual methods.

5.3 The precision and relative accuracy of the test results depend on the representativeness of the specimen or specimens, quality of specimen preparation, clarity of the grain boundaries (etch technique and etchant used), the number of grains measured or the measurement area, errors in detecting grain boundaries or grain interiors, errors due to detecting other features (carbides, inclusions, twin boundaries, and so forth), the representativeness of the fields measured, and programming errors.

5.4 Results from these test methods may be used to qualify material for shipment in accordance with guidelines agreed upon between purchaser and manufacturer, to compare different manufacturing processes or process variations, or to provide data for structure-property-behavior studies.

6. Interferences

6.1 Improper polishing techniques that leave excessively large scratches on the surface, or produce excessive deformation or smearing of the microstructure, or produce pull-outs and other defects, will lead to measurement errors, particularly when automatic image analyzers are employed.

6.2 Etching techniques or etchants that produce only partial delineation of the grain boundaries will bias test results and must be avoided.

6.3 Etching techniques or etchants that reveal annealing twins in certain face-centered cubic metals and alloys usually should be avoided if the grain size is to be measured by automatic image analyzers. The presence of twin boundaries can be tolerated when semiautomatic digitizing tablets are utilized but measurement errors are more likely to occur. Etching techniques and etchants that do not delineate twin boundaries are preferred for these specimens. Discrimination of grain boundaries but not twin boundaries using image amendment techniques may be possible with some automatic image analyzers. Such techniques may be employed if the operator can demonstrate their reliability. Each field evaluated using these methods should be carefully examined before (or after) measurements are made and manually edited, if necessary.

6.4 Image processing techniques employed to complete missing or incompletely developed grain boundaries, or to create grain boundaries in grain-contrast/color etched specimens, must be used with caution as false boundaries may be created in the former case, and grain boundaries may not be produced between adjacent grains with similar contrast or color in the latter case.

6.5 Inclusions, carbides, nitrides, and other similar constituents within grains may be detected as grain boundaries when automatic image analyzers are utilized. These features should be removed from the field before measurements are made.

6.6 Orientation-sensitive etchants should be avoided as some boundaries are deeply etched, others are properly etched, while some are barely revealed or not revealed at all. Excessively deep etching with such etchants to bring out the fainter boundaries should not be done because deep etching creates excessive relief (deviation from planar conditions) and will bias certain measurements, particularly grain intercept lengths and grain areas, performed by automatic image analysis and also measurements made with a digitizing tablet.

6.7 Detection of proeutectoid α grains in steels containing ferrite and pearlite (and other alloys with similar structures) by automatic image analyzers can result in detection of ferrite within the pearlitic constituent when the interlamellar spacing is coarse. Use of high magnifications accentuates this problem. For such structures, use the lowest possible magnification, or use semiautomatic devices.

6.8 Dust, pieces of tissue paper, oil or water stains, or other foreign debris on the surface to be examined will bias the measurement results.

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6.9 If photographic images are measured using a digitizing tablet, uncertainties in the magnification (particularly when enlargements are used) will bias the test results.

6.10 Vibrations, if present, can blur the image and bias test results and must be minimized or eliminated when using automatic image analysis.

6.11 Dust in the microscope or camera system may produce spurious detail in the image that may be detected as a grain boundary, particularly on automatic image analyzers, and will bias the test results. Consequently, the imaging system must be kept clean.

6.12 Nonuniform illumination can influence feature detection and thresholding using automatic image analyzers. Prior to analysis, center the light source (as described in the operating instructions for the microscope) and adjust the field and aperture diaphragms for best image clarity. Digital correction methods for nonuniform illumination may be used subsequently; however, these methods should not be used in lieu of proper microscope alignment and adjustment.

7. Apparatus

7.1 A high quality, research-type reflected light microscope is most commonly used to image the microstructure (images from electron metallographic instruments may also be used). If a digitizing tablet is utilized for the measurements, illumination modes other than bright field may be useful for certain specimens. For example, for optically anisotropic materials that are difficult to etch, crossed polarized light may be required to observe the grain structure. Such images exhibit grain contrast or color differences between grains rather than grain boundary delineation. These images, which usually exhibit low light intensities, can be measured using a digitizing tablet but may be more difficult to measure with automatic image analyzers.

7.1.1 If an automatic image analyzer is employed to perform the measurements, an upright-type metallurgical microscope is preferred over an inverted microscope due to the greater ease in observing the specimen surface with automatic stage movement.

7.2 A semiautomatic digitizing tablet with a measurement resolution of at least 0.1 mm can be used to measure the grain size. A variety of approaches can be employed. The simplest is to fix a photograph (usually an enlargement) to the tablet surface and place a suitable grid over the photograph (placement done without bias), tape down the corners of the grid, and use the cursor, fitted with fine cross hairs, to measure the appropriate features. Alternatively, the grid can be placed on an eyepiece reticle. The cursor is moved over the tablet surface and the microscopist can see the illuminated cross hairs in the cursor through the eyepieces over the field of view and grid pattern. A third approach is to transfer the microstructural image, test grid image and cursor image to a television monitor. The microscopist moves the cursor across the tablet surface while watching the monitor to make the appropriate measurements.

7.2.1 A variety of test grids, in the form of transparent sheets or as eyepiece reticles, may be utilized with a semiautomatic digitizing tablet. For counting grain boundary intersections or grains intercepted, a circular test grid, such as described in Test Methods E112, may be used. For measuring intercept lengths, a test grid with a number of equally spaced straight, parallel lines is used.

7.3 An automatic image analyzer with a camera of adequate sensitivity can be used to detect the grain boundaries, or grain interiors, and make the appropriate measurements.

7.3.1 A programmable automatic stage to control movement in the x and y directions without operator attention may be used, but is not mandatory. Use of a programmable stage prevents bias in field selection.

7.4 A computer, of suitable capability, is used with either a digitizing tablet or automatic image analyzer to store and analyze the measurement data. For automatic image analysis, the computer also controls all of the operations except, perhaps, focusing (automatic focusing is optional).

7.5 A printer is used to output the data and relevant identification/background information in a convenient format. Graphical data may be produced with either a printer or plotter, as desired.

7.6 This equipment must be housed in a location relatively free of airborne dust, particularly for automatic image analyzers. High levels of humidity must be avoided as staining of specimen surfaces may occur during, or before, analysis. Very low levels of humidity must also be avoided as static electricity may damage electronic components. Vibrations, if excessive, must be isolated, particularly for automatic image analysis.

8. Sampling

8.1 Specimens should be selected to represent average conditions within a heat lot, treatment lot, or product, or to assess variations anticipated across or along a product or component, depending on the nature of the material being tested and the aims of the investigation. Sampling location and frequency should be based upon agreements between manufacturers and users.

8.2 Specimens should not be taken from areas affected by shearing, burning or other processes that will alter the grain structure.

9. Test Specimens

9.1 In general, if the grain structure is equiaxed, any specimen orientation is acceptable. However, the presence of an equiaxed grain structure in a wrought specimen can only be determined by examination of a plane of polish parallel to the deformation axis. Consequently, preparation of longitudinally oriented specimens, where the plane-of-polish is parallel to the deformation axis or grain elongation direction, is recommended.

9.2 If the grain structure of a longitudinally oriented specimen is equiaxed, then grain size measurements on this plane, or any other, will be equivalent within the statistical precision of the test method. If the grain structure is not equiaxed but elongated, then grain size measurements on specimens with different orientations will vary. In this case the grain size must

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be determined on longitudinal, transverse, and planar surfaces, or radial and transverse surfaces, depending on the product shape, and averaged, as described in Annex A1, to obtain the mean grain size. If directed test lines (rather than random) are used for intercept counts on non-equiaxed grains in plate or sheet type specimens, the required measurements can be made using only two principle test planes, rather than all three, due to the equivalence of test directions, as described in A1.4.3 and A1.4.4.

9.3 The surface to be polished should be large enough in area to permit measurement of at least five fields, preferably more, at the necessary magnification. In most cases (except for thin sheet or wire specimens), a minimum polished surface area of 160 mm^2 (0.25 $in.^2$) is adequate.

9.4 Thin product forms can be sampled by placing one or more longitudinally oriented (or transverse, if required for non-equiaxed grain structures) pieces in the mount so that the sampling area is sufficient. Adjust the stage movement so that the interface between adjacent specimens is avoided, that is, is not in the field of measurement.

10. Specimen Preparation

10.1 Metallographic specimen preparation must be carefully controlled to produce acceptable quality surfaces for image analysis. Guidelines and recommended practices are given in Guide E3.

10.2 The polishing procedure must remove all deformation and damage induced by the cutting and grinding procedure. All scratches and smearing must be removed, although very fine scratches from the final polishing step can usually be tolerated. Scratches from grinding, or from polishing with abrasives larger than about 1-µm in diameter, must be removed. Excessive relief, pitting or pullout must be avoided. Specimens must be carefully cleaned and dried after polishing.

10.3 Specimens to be rated for grain size should be in the desired heat treated condition representative of the product, for example, solution annealed, annealed, as-quenched, or quenched and tempered. Other treatment conditions, such as as-hot rolled, as-hot forged, or as-cold drawn, may be tested as required but it must be recognized that the grain structure for these conditions may not be equiaxed.

10.4 Mounting of specimens is not always required depending on their size and shape and the available preparation equipment; or, if hand polishing is utilized for bulk specimens of convenient size and shape.

10.5 The polished surface area for mounted specimens should be somewhat greater than the area required for measurement to avoid edge interferences. Unmounted specimens generally should have a surface area much larger than required for measurement to facilitate leveling, if automatic image analysis is to be utilized, as described in 12.2.

10.6 Etching of specimens is a critical step in the preparation sequence. The choice of the proper etchant depends on the composition and heat treatment condition of the specimen. For automatic image analysis, a flat etch condition, that is, where the grain boundaries appear dark against a light matrix, is normally required. Practice E407 and Ref (**1**)[3] list many suitable etchants. A very high degree of grain boundary delineation is required.

10.7 A greater range of grain structure etchant types may be used for grain size measurement with a semiautomatic digitizing tablet. Grain contrast (**1**) and tint etchants (**1,2**) are very effective because they generally provide full delineation of the grain structure.

10.8 For certain specimens, for example, austenitic stainless steels, grain boundary delineation can be improved if the specimen is subjected to a sensitization treatment which precipitates carbides at the grain boundaries.

10.9 Specimens that contain annealing twins are difficult to measure for grain size because the twin boundaries are detected as well as the grain boundaries. For such specimens, semiautomatic digitizing tablet measurements are preferred. Certain electrolytic etching techniques, (**3,4**) as summarized in Ref (**1**) will delineate the grain boundaries but not the twin boundaries thus permitting use of automatic image analysis.

10.10 Specimens that have been carburized for grain size measurement according to the McQuaid-Ehn technique, as described in Test Methods E112, should be etched using a reagent that darkens the cementite preferentially, such as alkaline sodium picrate (see Practice E407, or Ref (**1**)) or Beraha's sodium molybdate tint etchant. (**1, 2**) Any cementite not present at a grain boundary is ignored, if a digitizing tablet is used, or deleted from the image prior to measurement, if automatic image analysis is used.

10.11 Delineation of prior-austenite grain boundaries in a hardened alloy steel specimen is quite difficult and usually requires considerable experimentation. The nature of the heat treatment is usually important, particularly the tempering temperature, if used. Subjecting the specimen to a temper embrittlement cycle may enhance the etch response, but this treatment is not helpful if the amounts of P, Sn, As, and Sb are very low. In general, coarse-grained specimens are more easily etched for prior-austenite grain size. Reference (**1**) provides guidance for development of prior-austenite grain boundaries. In general, it is difficult to reveal the prior-austenite grain boundaries to the level required for automatic image analysis, unless the image can be edited successfully prior to measurement, and measurements with a digitizing tablet may be preferable.

10.12 Heat treatments that precipitate a second-phase constituent along the prior-austenite grain boundaries in steel specimens may be useful. Again, this technique works best with relatively coarse-grained steels.

10.13 Image signal processing techniques, such as skeletonization (**5,6**) or watershed segmentation, (**6-8**) may be used to complete missing grain boundaries or produce grain boundaries in grain contrast etched specimens. However, these techniques must be used with caution because skeletonization can produce false grain boundaries and watershed segmentation

[3] The boldface numbers in parentheses refer to the list of references at the end of this standard.

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may not produce grain boundaries between two adjacent grains with similar color or gray level. Light pen, mouse, or trackball editing of images to complete missing grain boundaries before measurement is an acceptable technique, although slow.

10.14 Photomicrographs may be prepared, as described in Guide E883, for measurement with a digitizing tablet. If enlargements are used, the magnification must be determined to a precision of ±1 % maximum before measurements are made. A sufficient number of fields, selected blindly without bias, must be photographed at the required magnification to ensure adequate statistical precision.

10.15 Annex A2 shows micrographs of a variety of metals and alloys exhibiting properly and improperly etched grain structures with comments concerning their suitability for subsequent analysis using either a semiautomatic digitizing tablet or an automatic image analyzer.

10.16 Annex A1 describes methods for determining the grain size of specimens with nonequiaxed grain shapes, as well as procedures for defining the grain anisotropy index (degree of grain elongation).

11. Calibration and Standardization

11.1 Use a stage micrometer to determine the true linear magnification for each objective and eyepiece combination to be used.

11.2 Determine the magnification of photomicrographs by photographing the stage micrometer image and dividing the magnified length of the micrometer scale by the true length.

11.3 If enlargements are made from photographic negatives, set up the enlarger using the negative of the micrometer scale and determine the magnification of the enlarged micrograph in the same manner as described in paragraph 11.2. Then, make enlargements of the grain structure images using the same enlarger setting. Alternatively, determine the degree of enlargement by comparing the size of features on the enlargement to their size on the contact print. Repeat this process for a number of features in the image. Determine the average enlargement factor of the measured features and multiply this value by the magnification of the contact print.

11.4 If a video monitor is used with a semiautomatic digitizing tablet, determine the video monitor magnification for each objective and projection eyepiece/camera multiplying factor combination using a stage micrometer scale.

11.5 If an automatic image analyzer is used, determine the size of the test area or magnification bar using a stage micrometer scale for each objective and projection eyepiece/camera multiplying factor combination (consult the manufacturer's instruction book for the calibration procedure specific to the instrument used).

11.6 Use a ruler with a millimetre scale to determine the actual length of straight test lines or the diameter of test circles used as grids.

11.7 Use a stage micrometer to measure the length of straight test lines or the diameter of test circles on eyepiece reticles.

11.8 When a video camera is employed, follow the manufacturer's recommendation in adjusting the microscope light source and setting the correct level of illumination for the particular camera used.

11.9 For automatic image analysis measurements, use the flicker method of switching back-and-forth between the live video image and the detected image of either the grain boundaries or grain interiors to establish the correct setting of the gray-level threshold controls, as described in 13.3.

12. Procedure: Semiautomatic Digitizing Tablet

12.1 When photomicrographs are used for measurements, choose the magnification so that at least fifty grains, preferably more, are present, unless the grain structure is extremely coarse. Avoid an excessively high number of grains per photograph as counting accuracy may be impaired. To minimize operator fatigue, and to ensure measurement accuracy, the smallest grain on the photomicrograph should be about 5 mm in diameter. Take the micrographs at random, that is, without bias in the field selection, and prepare a sufficient number, at least five, to obtain adequate statistical precision. Fix each micrograph to the tablet surface, for example using masking tape, to prevent movement during analysis. Drop the measurement grid onto the photograph to prevent placement bias. Tape the grid corners to the micrograph or tablet surface to prevent movement during measurement.

12.2 When a microscope is used to produce the image of the grain structure for subsequent measurement, using either a semiautomatic or automatic image analyzer, place the specimen on the microscope stage so that its surface is perpendicular to the optic axis. With an inverted-type microscope, simply place the specimen face down on the stage plate and hold it in place with the stage clamps. With an upright-type microscope, place the specimen on a slide and level the surface using clay or plasticene between the specimen and slide. To avoid problems with adherent tissue paper, follow the alternate leveling procedure described in Practice E1245 (Procedure section).

12.2.1 The microscope light source should be checked for correct alignment and the illumination intensity should be adjusted to the level required by the television camera.

12.2.2 When a live microscopical image is used, either with a digitizing tablet, or an automatic image analyzer, field selection should be done blindly without bias. Never attempt to choose" typical" or "worst" fields (except for the ALA method, see 12.6.1) as bias will be introduced. For manual stage movement, move the x- and y-stage controls without looking at the image. If a programmable stage is available, set the stage controls to sample the image in a systematic manner. Measurement fields should not be overlapped.

12.2.3 To obtain a reasonable degree of measurement precision, it is not necessary to sample a large number of fields. Generally, from five to twenty fields are adequate (see the comments about the number of fields or measurements required for each type of measurement described in the following sections).

12.2.4 Adjust the magnification of the system so that at least 50 grains, preferably more (unless the grain structure is

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extremely coarse), are observed through the eyepieces or on the television monitor. If an excessively high number of grains are present in the image, measurement precision will be impaired. For accurate measurement of intercept lengths or grain areas, the smallest grains should be at least 5 mm in diameter on the television monitor (**9**) (for a typical 305 mm–330 mm (12 in.–13 in.) diameter monitor).

NOTE 1—For automatic image analyzers with a pixel density substantially greater than the commonly used 512 × 512 array, grains somewhat smaller than 5 mm in diameter (on the monitor screen) may be measured with reasonable precision. The operator must determine the minimum apparent size grain that can be measured with a deviation of no more than 10 % of the diameter or 20 % of the area using test circles or squares of known size (see Ref. (**9**) for an example of this procedure).

12.2.5 When a semiautomatic digitizing tablet is used with a live microscope image and an eyepiece test grid reticle, select the appropriate reticle for measurement and adjust the magnification so that about 50 grains are visible, unless the grain size is extremely coarse. Counting accuracy will be impaired if the number of grains visible is excessively high (smaller apparent size in the field of view).

12.2.6 The grain size measurement methods described in the following paragraphs are those known to produce accurate results with reasonable precision and minimal bias. There may be other possible methods, or other equivalent procedures, that can be used to measure grain size. The operator should evaluate the precision and accuracy of such methods on specimens carefully evaluated by one or more of the recommended methods before utilizing an alternate method or procedure. It should be recognized that slight differences in grain size ratings may be obtained using different methods because different aspects of the grain structure are being assessed. Also, minor deviations from equiaxed conditions may accentuate these differences. Methods based on the average grain area or the number of grains per unit area are directly related to the total length of grain edges per unit volume, L_V. Methods based on the mean intercept length or the number of grain boundary intersections per unit length are directly related to the grain boundary surface area per unit volume, S_V. Hence, because these methods are based upon two different geometrical characteristics of the grain structure, minor grain size differences may result when the planar grain size is determined using methods based on L_V vs. S_V .

12.3 *Intercept Length Method:*

12.3.1 When a digitizing tablet is used to measure grain intercept lengths using a template consisting of parallel straight test lines, as described in 12.3.2, measure only the lengths of the test lines that intersect grains (that is, measure the chord distances between successively intersected grain boundaries). Generally, each test line will begin and end within a grain and these partial chords are not measured (see Table 1).

12.3.2 The test grid, consisting of a number of parallel, straight test lines with a spacing greater than the apparent mean grain diameter, should be randomly superimposed over the photographic or live image, without bias, at two or more orientations to average any anisotropy that may be present. If the grain structure is clearly elongated, four different orientations with respect to the longitudinal direction, for example, 0°, 45°, 90° and 135°, should be used as described in the Appendix in Test Methods E1181. This procedure should be repeated on each of at least five photomicrographs or live microscope images, each randomly selected, until at least 500 grain intercept lengths (chords) are measured. If the degree of grain elongation (grain anisotropy) is of interest, use grid line orientations of 0° and 90° with respect to the deformation direction of the specimen. The degree of grain elongation, or anisotropy, is the ratio of the average intercept lengths parallel to the deformation direction (0°) to the average intercept length perpendicular to the deformation direction (90°). Annex A1 provides information concerning the measurement of grain size and grain anisotropy for non-equiaxed grain structures.

12.3.3 The average intercept length, $\bar{l}$, is calculated from the number of measured values, N, of l_i using true length units (µm or mm) by dividing the apparent length on the photomicrograph or microscope image by the magnification, M.

TABLE 1 Summary of Counting/Measuring Restrictions for Semiautomatic and Automatic Image Analysis Methods

Method	Paragraph	Measurement	Restrictions
		Semiautomatic Image Analysis Methods	
Intercept Lengths	12.3	l_i	Measure only whole intercept lengths, ignore intercepts that end within a grain.
Intercept & Intersection Counts	12.4	P_{Li}, N_{Li}	No restrictions except for the diameter of a circular test grid; the number of grains per field.
Grain Count	12.5	N_{Ai}	Count only whole grains within a known test area.
Grain Area	12.6.1	Ai	Measure areas of whole grains only.
ALA method	12.6.2	A_{max}	Measure entire area of the largest observed grain section.
Two-Phase Methods	12.7.1	$l_{\alpha i}$	Measure only whole intercept lengths, ignore intercepts that end within a grain.
Two-Phase Methods	12.7.2	$A_{A\alpha}$, $P_{P\alpha}$ N_α	No restrictions.
		Automatic Image Analysis Methods	
Grain Boundary Length/ Area	13.5.1	L_{Ai}	No restrictions as long as the field contains a large number of grains.
Intersection Counts	13.6.1	P_{Li}	No restrictions as long as the field contains a large number of grains.
Intercept Lengths	13.7.1	$\bar{l}_i$, l_i	Measure only whole intercept (chord) lengths, delete grains intersecting the test area border.
Grain Count	13.8.1	N_{Ai}	Count only whole grains within a known test area.
Grain Areas	13.9.1	$\bar{A}_i$, A_i	Only whole grains should be in the test area.
ALA Method	13.9.9	A_{max}	Measure the entire area of the largest observed grain section.
Two-Phase Methods	13.10	$\bar{l}_\alpha$,$\bar{A}_\alpha$	Measure only whole intercept (chord) lengths or whole grain areas.

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12.3.4 A histogram of the intercept lengths may be constructed to determine or illustrate the uniformity of the grain intercept lengths and to detect and analyze duplex grain size conditions. The analytical method is described in Test Methods E1181, Appendix X2.

12.3.5 Calculate the standard deviation, s, of the individual intercept measurements. Most digitizing tables have software programs established for such computations. If the histogram reveals a duplex condition, calculate s for the intercepts within each region of the distribution curve. To do this, sort the intercept lengths in ascending order, separate the data into the two individual distributions, and compute $\bar{l}$ and s for the intercept lengths in each distribution. Such a computation is easy to perform if the data can be read into a spreadsheet type computer program.

12.4 *Intercept and Intersection Count Methods:*

12.4.1 A digitizing table can be used to count the number of grain boundary intersections, P_i, or the number of grains intercepted, N_i, (the former is preferred) by a circular test grid in the same manner as described for manual measurements of P and N in Test Methods E112.

12.4.2 The test grid or reticle should be a circle, or three circles as described in Test Methods E112. Although any size circle can be used, as long as the circle is larger than the largest grain in the field, relatively small circles are not recommended as the efficiency of the analysis is impaired. In general, the same recommendations as in Test Methods E112 apply, that is, use a test circle or three concentric circles with a total line length of 500 mm. The average number of intercepts or intersections should be about 100, with a minimum of 70 and a maximum of 150 (unless the grain size is too coarse). This ideal range may not always be achievable depending upon the available magnification steps, and values outside this range may be used in such cases (the number of fields measured should be changed to achieve the counting total described in 12.4.3). When using an eyepiece reticle, use of a single test circle, of diameter significantly larger than the largest grain, is recommended to minimize operator fatigue. In this case, the average number of intercepts or intersections should be at least 25 per circle.

12.4.3 Repeat the analysis until at least 500 grain boundary intersections or grain interceptions have been counted on five or more randomly selected fields or photomicrographs. If five photomicrographs are used and one placement per photograph is insufficient to produce at least 500 counts, repeat the measurements using different regions of the same photomicrographs. For example, if the number of counts for the first grid placement on micrograph one is significantly below 100, drop the grid on a second region of the micrograph and repeat the measurement until about 100 counts are obtained per micrograph. This is easily performed, without producing bias, if enlargements are used. Alternatively, a greater number of micrographs can be made and analyzed. When using a live microscope image and an eyepiece reticle, simply select more fields, at random, until at least 500 total counts are made.

12.4.4 Grain boundary intersections and grains intercepted can also be counted using a test grid composed of straight test lines. However, because of the problems associated with counts at the ends of the test lines, this practice is not recommended unless half intercepts or intersections can be tallied separately. For such work, follow the counting rules described in Test Methods E112.

12.4.5 With a circular test grid, end counting problems are eliminated. When counting grain boundary intersections, which is usually easier, a tangential intersection with a grain boundary is counted as one intersection. Each grain boundary cut by the test line is also counted as one intersection. Count an intersection of the junction of three grains, a "triple point", as 1½ intersections. If the cursor can be programmed to record each triple point intersection as 1½, count these separately. If this cannot be done, count every other triple point intersection twice. If the test line should intersect a junction between four grains, which occurs rarely, count this intersection twice, that is, as 2 intersections.

12.4.6 For each test circle (or concentric circles) placement, determine P_{Li} or N_{Li} by dividing the number of intersections, P_i, or the number of intercepts, N_i, by the true test line length, that is, the true circle circumference, L_{ti}:

$$P_{Li} = \frac{P_i}{L_{ti}} \tag{1}$$

or,

$$N_{Li} = \frac{N_i}{L_{ti}} \tag{2}$$

where:

$$L_{ti} = \frac{\pi d}{M} \tag{3}$$

for a single circle of diameter d; or,

$$L_{ti} = \frac{(\pi d_1) + (\pi d_2) + (\pi d_3)}{M} \tag{4}$$

for three concentric circles of diameter d_1, d_2, and d_3 and magnification M.

12.4.7 Next, calculate the mean values $\bar{P}_L$ or $\bar{N}_L$, for N fields measured, or n grid placements.

12.4.8 Then, determine the mean lineal intercept length, $\bar{l}$:

$$\bar{l} = \frac{1}{\bar{P}_L} = \frac{1}{\bar{N}_L} \tag{5}$$

where $\bar{l}$ is in µm or mm.

12.4.9 Calculate the standard deviation, s, of the individual measurements of P_{Li} or N_{Li}.

12.5 *Grain Count (Planimetric) Method:*

12.5.1 Grain size may also be determined by the Jeffries planimetric procedure using a digitizing tablet and several procedures may be used. However, as with manual application of the Jeffries method, the tablet method also requires marking off of the grains in order to obtain an accurate count. Hence, the method is less efficient than the intercept procedures. Because of the need to mark off the grains as they are counted, this method is best utilized with photomicrographs.

12.5.2 Prepare at least five photomicrographs, taken randomly. Enlargements are easiest to use. Each micrograph should contain at least fifty whole grains, unless the grain size is extremely coarse. On each micrograph, mark off the number

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