Designation: C 1652/C 1652M – 06

Standard Test Method for Measuring Optical Distortion in Flat Glass Products Using Digital Photography of Grids[1]

This standard is issued under the fixed designation C 1652/C 1652M; 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

Transmitted and reflected distortion in annealed, heat strengthened, and tempered glass can be measured by several methods.(**1**,**2**,**7**,**8**,) [2] Qualitative methods are based on the observation of waviness in the glass as viewed in of reflected or transmitted images in a set of equidistant lines, called Zebra Lines. Quantitative measuring techniques are based on several methods, some of which are:
1) Measuring local curvature using mechanical radius gages ((**1**, **6**,**9**)
2) Moire Fringe analysis (**3**, **4**)
3) Double exposure of transmitted grid images (Practice F 733)
4) Projection of an array of round dots (**5**)
5) Dual laser beams (**10**)
The user should be familiar with techniques that are available so as to select the most suitable after considering the precision, speed, and test specification requirements. The test method described in this document uses a digital camera to capture a transmitted or reflected image of a set of equidistant lines. Changes in the spacing of lines are used to quantifying the distortion.

1. Scope

1.1 This test method covers the determination of optical distortion of heat-strengthened and fully tempered architectural glass substrates which have been processed in a heat controlled continuous or oscillating conveyance oven. See Specifications C 1036 and C 1048 for discussion of the characteristics of glass so processed. In this test method the reflected image of processed glass is photographed and the photographic image analyzed to quantify the distortion due to surface waviness. The test method is also useful to quantify optical distortion observed in transmitted light in laminated glass assemblies.

1.2 The values stated in either SI units or inch-pound units are regarded separately as standard. 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 the standard.

1.3 There is no known ISO equivalent to this standard.

1.4 *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:* [3]

C 162 Terminology of Glass and Glass Products
C 1036 Specification for Flat Glass
C 1048 Specification for Heat-Treated Flat Glass—Kind HS, Kind FT Coated and Uncoated Glass
F 733 Practice for Optical Distortion and Deviation of Transparent Parts Using the Double-Exposure Method

3. Terminology

3.1 See Terminology C 162 Terminology of Glass and Glass Products

3.2

3.2.1 *focal length, F*—The focal length of a specular reflector, due to the curvature at a point equals R/2. (See 3.2.3.) In transmitted light, local thickness changes introduce a convergence or divergence, equivalent to a lens with a focal length F.

3.2.2 *optical power, D*—The optical power due to the curvature at a point is D = 1/F. The optical power is expressed

[1] This test method is under the jurisdiction of ASTM Committee C14 on Glass and Glass Products and is the direct responsibility of Subcommittee C14.11 on Optical Properties.

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

[3] 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.

in diopters, (Units 1/m), or as is typical, in millidiopters. The optical power is also used to quantify optical distortion, the deformation of images reflected from flat glass, or transmitted by laminated or bent glass, or both.

3.2.3 *radius of curvature, R*—The local radius of curvature at a point on the surface, in meters. R_x and R_y are respectively measured in planes x (usually horizontal) and y (usually vertical)

3.2.4 *roll wave*—A repetitive, wave-like departure from flatness in otherwise flat glass that results from heat-treating the glass in a horizontal conveyance system. Roll wave excludes edge effects such as edge kink, and distortion induced by assembly or installation.

4. Summary of Test Method

4.1 This test procedure was designed to provide an accurate method of quantifying the optical distortion of glass as it is revealed in reflected or transmitted images. The optical distortion in reflected light can be related to a surface waviness, known as roll wave in tempered glass products, or, in transmitted light, related to curvature and local thickness variations in laminated glass products. The test method is based on the use of a digital camera which is used to record the appearance of an accurately printed grid pattern which has been reflected from or transmitted though apiece glass. Mathematical analyses performed on computer of the changes in the grid pattern along with the laws of optics and the geometrical arrangement makes it possible to quantify the lens power or optical distortion of each element of the glass surface defined by the grid.

4.2 A uniformly spaced set of parallel lines, usually set at 45° angle to horizontal, may be used instead of a grid. If such a set of lines is used, the mathematics of calculation will be slightly altered from those expressed in Appendix X1.

5. Significance and Use

5.1 This test provides accurate data for evaluation of the optical properties of the glass being inspected.

5.2 The procedure described is useful for measuring the roll wave introduced during the tempering process of flat architectural glass. (1)

5.3 This test method is also useful for inspection of laminated and tempered automotive glass in transmitted light, in both flat and curved geometries.

6. Apparatus

6.1 The items shown in Fig. 1 are required to practice this test method:

6.2 An accurately printed flat screen containing a pattern of equidistant black lines on a white background.

NOTE 1—The ruled area of the screen should have at least twice the dimensions of the area on the glass to be examined.

6.2.1 The line spacing or pitch p (center to center or corresponding edge to corresponding edge distance between adjacent lines) defines the spatial resolution of the system. A 50 mm [2 in] pitch in both horizontal and vertical directions provides satisfactory resolution for the examination of tempered glass in reflection mode. A smaller pitch can be used when examination of smaller deformations in laminated glass is carried out using this test method. The width of the black line is typically 6 mm [¼ in]. The line-to-line distance must be uniform, in both horizontal and vertical directions. The uniformity of the line-to-line spacing, p, is critical, because the

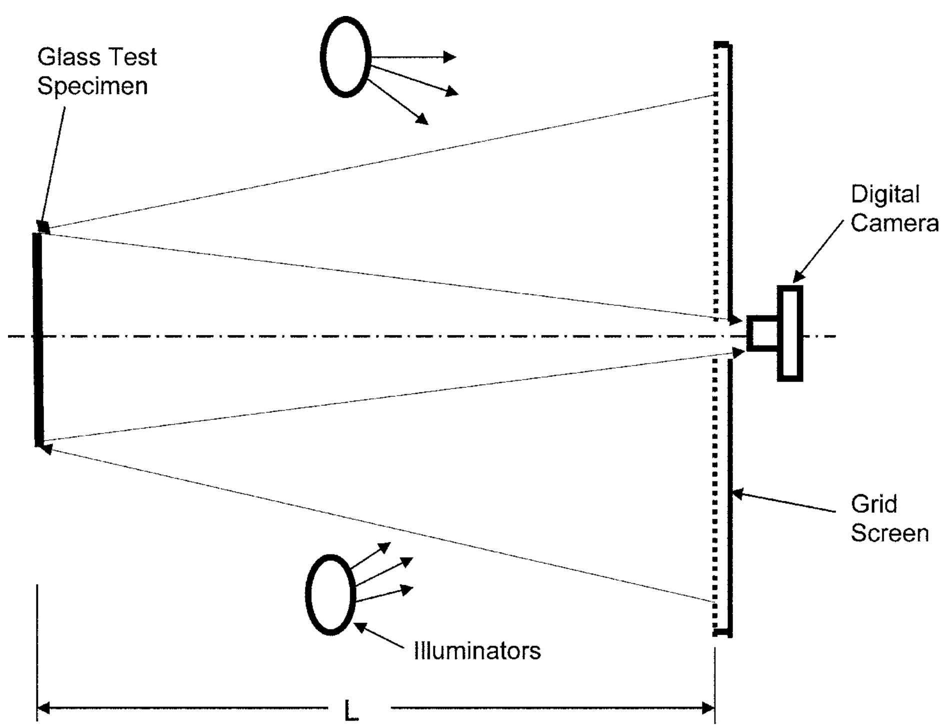

FIG. 1 Test Configurations of Reflective Analysis

system interprets a non-uniform spacing as optical distortion. A uniformity of the pitch of 0.2 mm [0.008 in] is satisfactory in reflective measurements.

6.3 A digital camera equipped with an a planar lens and an image pixel resolution compatible with the software requirements. These requirements are met by most commercially available digital cameras.

6.4 A computer using an operating system compatible with the software and any peripherals needed to satisfy the data logging and reporting requirements.

6.5 A software program capable of performing the evaluation of changes in line-spacing, p, and computation of the optical distortion, D, throughout the inspected region.

6.6 Lighting sufficient to provide photographic contrast.

6.6.1 A uniform illumination of the screen must be ensured. In average lighting conditions, four Quartz-Halogen floodlamps, 500 watt each, are satisfactory.

6.6.2 In a brightly illuminated area, two times higher illumination power is needed to assure good photographic contrast.

7. Sampling

7.1 The number of specimens and frequency of testing is to be determined by the user.

8. Calibration and Standardization

8.1 System calibration is a two-step procedure.

8.2 *Verification of System Zero*

8.2.1 Set the camera at a distance 2L from the screen. Capture the image of the screen without a glass panel in place and process the image through the analysis software. The image analysis should indicate small values of D throughout the inspection area, typically less than 5 mdpt.

8.3 *Verification of Calibration (Span Calibration)*

8.3.1 This system calibration is determined by the screen uniformity and distance, L, to the camera as shown in Fig. 1, Fig. 2, and Fig. 3.

8.3.2 Place a panel with known distortion in the test position. Record the screen image and process it through the software. The calculated distortion should not differ from the known value by more than 5 mdpt.

8.3.3 The known value of distortion should be established using traceable, curvature measuring methods. Dual laser beam and interferometry are suitable for this purpose.

9. Procedure

9.1 *Set up the grid screen*:

9.1.1 Ruled screen board should be vertical, in an upright position.

9.1.2 When used in reflective mode, the board should have a hole, sufficient for viewing through with a digital camera, cut in its center.

9.1.3 When the screen is wall-mounted, so that viewing through a hole in its center is not possible, the camera can be mounted next to the screen or above it. In this configuration (see Fig. 2), a V-shaped line drawn from the center of the glass to the center of the screen (L_1), and from the center of the glass to the center of the camera lens (L_2) represents a geometric, specular reflection. The screen must be perpendicular to the bisector of line L_1 and L_2 and the camera back must be perpendicular to line L_2.

9.1.4 The grid board typically should be somewhat larger than twice the dimensions of the glass to be measured. For example, to analyze a 600mm by 1200 mm [24 in by 48 in] glass, use a 1500 mm by 2500 mm [60 in by 100in] grid board.

9.2 *Set up the glass sample*:

9.2.1 Place the glass parallel to the grid board as shown in Fig. 1, at a measured distance L. The distance should be the

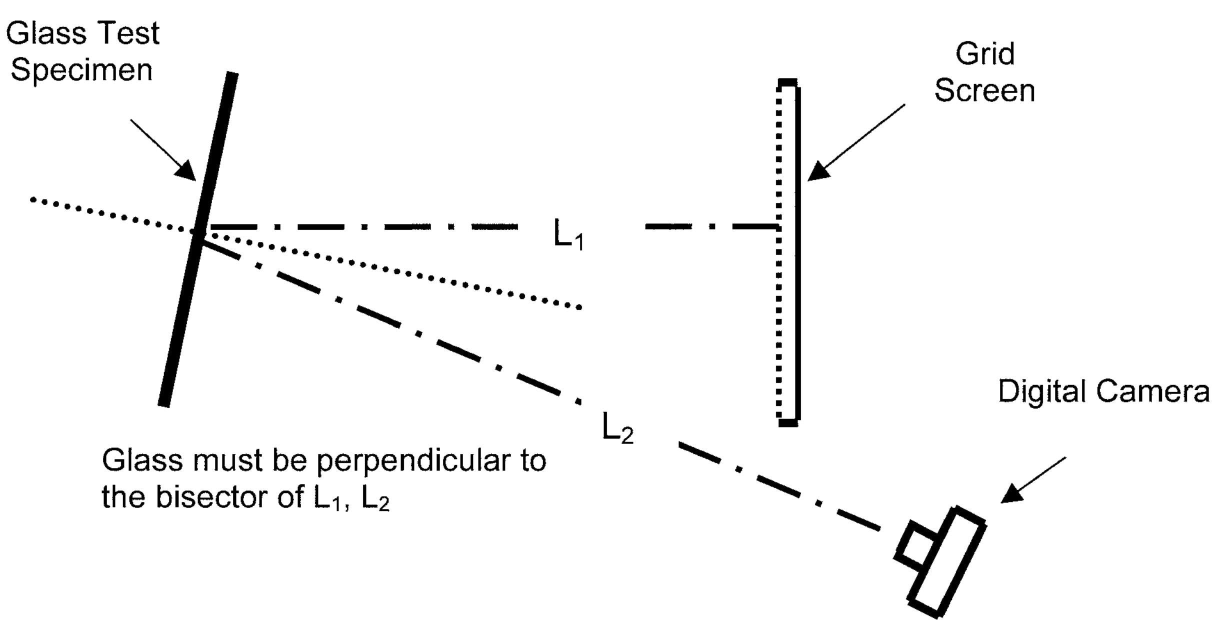

FIG. 2 Test Configuration for Off-Set Camera

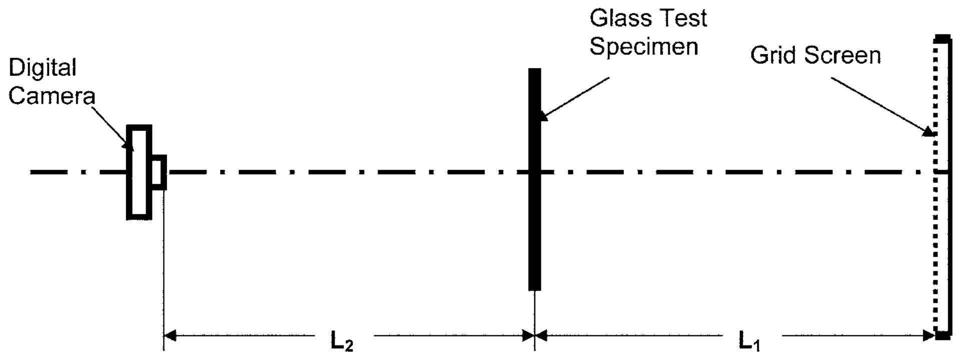

FIG. 3 Test Configuration in Transmitted Light

largest available, since the sensitivity of the measurement is directly proportional to the spacing, L. Four meters [160 in] yields satisfactory results.

9.2.2 For simplicity of computations, the overall distance between the screen and the camera should be L, so that, L_1= L_2= L. Nevertheless, the distances are not required to be equal.

9.2.3 Visually inspect the reflected image to assure that the roll wave is oriented horizontally or vertically. Fig. 3 illustrates the transmitted light set-up.

9.3 *Set up camera*:

9.3.1 Mount a digital camera on a suitable tripod, as shown in Fig. 2, and Fig. 3.

9.3.2 Set the camera to a resolution compatible with the software. Make sure that the image of the screen is in very sharp focus. In the image, the edges of the rectangular screen should be parallel to the edges of the camera frame.

9.4 *Illuminate grid screen*:

9.4.1 The illumination should be sufficient that good contrast is seen in the image. Use four 500-watt quartz flood lamps as specified in 6.6.1, placing them at an angle to the screen as illustrated in Fig. 1. Verify that the lights are not located in the field of view of the camera.

9.5 *Check out the set up*:

9.5.1 Place the glass to be analyzed in the field of view of the camera looking through the hole in the center of the grid board.

9.5.2 Make sure that all of the glass shows a reflection of the grid and that the grid and glass are on the same centerline and are parallel.

9.5.3 Visually inspect the reflected image to assure that the roll wave is oriented horizontally or vertically.

9.5.4 Assure a sharp focus.

9.5.5 Add an identification number for the glass by printing with a felt marker on an erasable board just above or below the sample, or by placing a printed label on the screen.

9.6 *Take a photograph*:

9.6.1 Take a digital photograph of the grid board pattern reflected from the glass or transmitted through it.

9.6.2 Transfer the camera images to a computer file, or to the software program.

10. Calculations and Analyses

10.1 Follow the software manufacturer's manual to perform the image analysis. The software should provide the full-field information on the optical distortion of the inspected item in tabular and graphical formats.

10.2 Save the results to satisfy the reporting requirements listed in Section 11.

10.3 When the test objective includes measuring of the roll wave distortion, the analysis must be performed along lines perpendicular to the roll wave direction.

10.4 Additional information may be presented in many ways including the maximum distortion within the limits of inspected area, both for the positive and the negative lens power.

10.5 A Graphical, 3D presentation and a table of values for each grid element on the sample is available in image analysis software.

10.6 Data, photos, and a quality summary comparing the results to specified performances is saved in a database in the computer for future reference.

10.7 The glass surface may be analyzed for (either or both):

10.7.1 Cylindrical lens power (uniaxial analysis), typically used when measuring the roller wave distortion of flat glass

10.7.2 Visual perception (biaxial analysis), typically used when measuring the optical distortion of laminated and curved items in transmitted light.

11. Report

11.1 From the measured changes in line spacing, the software calculates the uniaxial or biaxial optical power, or both, D, a teach point, using equations shown in Appendix X1.

11.2 For the roll wave analysis, the maximum optical power D and the location of maximum distortion within the inspection area must be calculated and reported. The report must include:

11.2.1 Date of the test,

11.2.2 Description of the item (Part ID, Serial #, Lot #),

11.2.3 Inspected area,

11.2.4 Screen pitch, p,

11.2.5 Distance, L, used in the test,

11.2.6 Type of analysis, uniaxial or biaxial,

11.2.7 Mean optical power,

11.2.8 Standard deviation of the optical power within a sample,

11.2.9 The software used, and,

11.2.10 Graphs or photographs or both, of deformed set of lines.

11.3 When inspecting laminated or bent glass, or both, in transmission, additional information may be required by the specification for the part under inspection.

12. Precision and Bias

12.1 The C14.11 Subcommittee will conduct an inter-laboratory Round Robin Test to determine the Precision and Bias of this test method

13. Keywords

13.1 flat glass; fully tempered glass; heat-strengthened glass; heat treated glass; optical distortion; roll wave

APPENDIXES

(Nonmandatory Information)

X1. COMPUTATION OF THE OPTICAL POWER FROM DISTORTED GRID IMAGES

X1.1 Consider the locally deformed reflecting surface shown in Fig. X1.1, for which the reflected angles of parallel incidence change along the reflecting surface. For two points on the reflector separated by a distance, p, the change in reflected angle, r_n, is related to the radius of curvature, R, of the surface by the following equation:

$$1 / R = (r_1 - r_2) / p \tag{X1.1}$$

X1.2 If p is the distance between lines of a uniform grid in the x y-plane, then Δp is the measured change of grid spacing as measured at a distance, L, from the distorted surface. The change in reflected angle is given by:

$$(r_1 - r_2) = \Delta p / L \tag{X1.2}$$

X1.3 Combining equations Eq X1.1 and X1.2 yields:

$$1 / R = (\Delta p / p) / L \tag{X1.3}$$

X1.4 The Focal Length, F, the distance from the reflecting surface to the point of convergence) in the horizontal direction, x, is:

$$F_x = R_x / 2 \tag{X1.4}$$

X1.5 In the vertical direction, y, perpendicular to x, identical computation yields:

$$F_y = R_y / 2 \tag{X1.5}$$

X1.6 Now the optical power which for flat glass is also called the optical distortion, D, is:

$$D = 1/F = 2/R = 2(\Delta p / p) / L \tag{X1.6}$$

X1.7 So that:

$$D_x = 1/F_x = 2/R_x = 2(\Delta p_x / p_x) / L \tag{X1.7}$$

$$D_y = 1/F_y = 2/R_y = 2(\Delta p_y / p_y) / L \tag{X1.8}$$

X1.8 In preceding equations, L is expressed in meters and D in diopters (1/m), abbreviated dpt. To express the distortion in mdpt, (millidiopters) the calculated values must be multiplied by 1000. When using the inch as unit of length, equations (Eq X1.6-X1.8) become:

$$D_x = (2{*}39.37)\,(\Delta p_x / p_x) / L \tag{X1.9}$$

X1.9 In equation Eq X1.9, D_x is the distortion in direction x, in dpt, Δp_x is the measured change in the grid spacing in the direction of the roll wave in inches, p_x is the average spacing

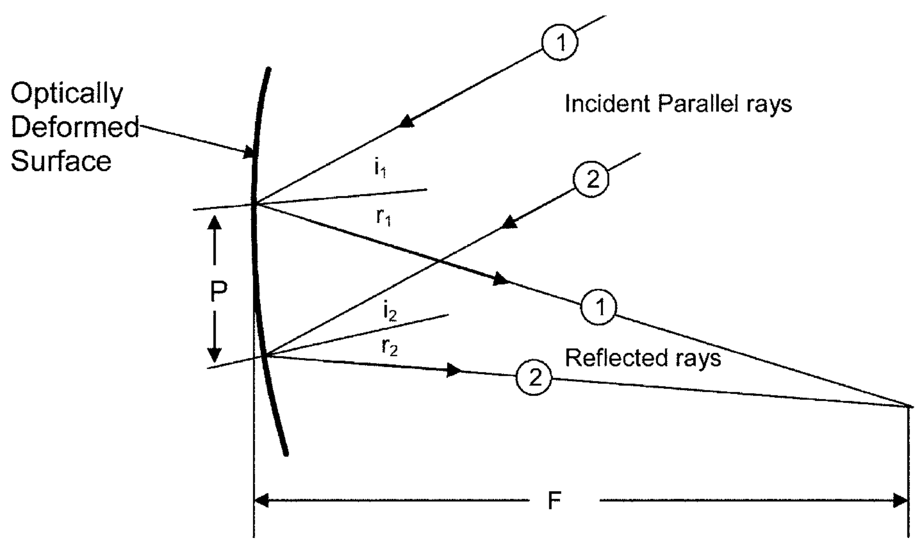

FIG. X1.1 Reflections from an Optically Distorted Surface of an undistorted grid in inches and L is the distance from the camera to the grid, also in inches.

X2. CALCULATION OF ROLL WAVE DISTORTION

X2.1 For tempered glass exhibiting roll wave, a series of parallel ridges and valleys form the generally sinusoidal surfaces. In this case, the maximum D_x(or D_y) occurs at peaks and valleys of the wavy surface. When the direction Y is parallel to the wave ridges and valleys, D_y remains small throughout.

X2.2 For roll wave analysis, the appropriate software can also calculate the peak to peak distance or wavelength λ of the wave. From the measured distortion D_x, and the wavelength, λ, the peak-to-valley height of the wave, W, is calculated using :

$$W = (D_x * \lambda^2) / 4\pi^2 \quad \text{(X2.1)}$$

X2.3 When the optical distortion is measured in laminated glass, or in any item that does not exhibit a set of cylindrical waves running in direction x or y, the values of D_x and D_y are measured individually. Maximum distortion can occur in any plane between x and y. This typically occurs in windshields where the maximum distortion is observed near the curved edges, oriented at an angle relative to directions x and y. Eq X1.1-X1.8 of Appendix X1 remain unchanged, but a more detailed analysis and calculations are needed for evaluation of the optical distortion and changes of grid angles. In this case a software manual or the equipment supplier should be consulted.

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