Designation: E1544 – 99 (Reapproved 2004)ε1

Standard Practice for Construction of a Stepped Block and Its Use to Estimate Errors Produced by Speed-of-Sound Measurement Systems for Use on Solids[1]

This standard is issued under the fixed designation E1544; 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.

ε1 NOTE—The correct Figure 2 was reinstated in May 2004.

1. Scope

1.1 This practice provides a means for evaluating both systematic and random errors for ultrasonic speed-of-sound measurement systems which are used for evaluating material characteristics associated with residual stress and which may also be used for nondestructive measurements of the dynamic elastic moduli of materials. Important features and construction details of a reference block crucial to these error evaluations are described. This practice can be used whenever the precision and bias of sound speed values are in question.

1.2 *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]

E650 Guide for Mounting Piezoelectric Acoustic Emission Sensors

E494 Practice for Measuring Ultrasonic Velocity in Materials

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *path length*—length of track along which the sound waves actually propagate.

3.1.2 *time of flight*—the measured time interval between the launching of a sonic input pulse at the start of a path and the time of reception of the pulse at the end of the path of travel.

3.1.2.1 *Discussion*—There are many different techniques used to avoid termination errors related to electronic delays and termination impedance effects and end interference. One commonly accepted procedure is to make the time measurement between successive echoes instead of using the electrical driving pulse as the start marker. Reference techniques that use two nearly identical sets of experiments, where one is the reference and the other the unknown and in which the difference in time of travel is the output result, cancel out many of the errors mentioned above (**1**).[3]

4. Summary of Practice

4.1 The physical quantity, speed of sound of a particular solid, is not a fundamental constant because it depends on separate measurements of time and distance. It is a computed value derived from measured values of distance and of time and is based on assumptions about the elastic material through which the sound waves travel. Because this quantity is not a fundamental property (dependent upon many other variables besides time and distance) of any material, a reference standard having a specific value of speed of sound is virtually impossible to construct. Thus, questions of accuracy have to be addressed in a different way.

4.2 The measurement of sound speed depends upon many factors. Considerations of the uniformity of both the elastic and the density characteristics of the material, of internal scattering, of transducer coupling and loading, of temperature uniformity and value, of external pressure and stress, and of many other physical effects that would alter the overall measurement process must be taken into account. Because the speed of sound is affected by so many physical parameters, the only available test to evaluate the detrimental influence of these higher order variables is to examine their combined effects on measured speed of sound values as it relates to the definition:

$$V = L/t \tag{1}$$

4.2.1 This defining equation for the sound speed, V, states a constant relationship between path length, L, and time of flight,

[1] This practice is under the jurisdiction of ASTM Committee E-28 on Mechanical Testing and is the direct responsibility of Subcommittee E28.13 on Residual Stress Measurement.

Current edition approved April 1, 2004. Published MAy 2004. Originally approved in 1993. Last previous edition approved in 99 as E1544 – 99. DOI: 10.1520/E1544-99R04E01.

[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.

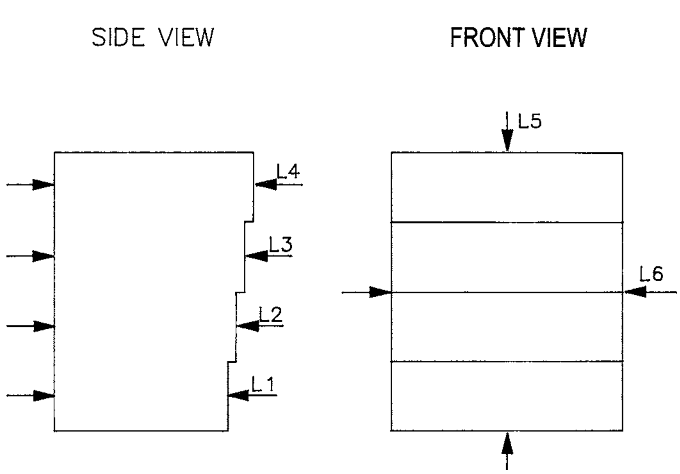
[3] The boldface numbers in parentheses refer to a list of references at the end of the text.

t, and is applicable primarily to methods in which the time is measured directly (**2**).

4.3 Several different methods of measuring speed of sound exist. A number of these are itemized in Practice E494. (McSkimin details many ingenious methods in Ref (**1**)). Regardless of the method used to calculate the sound speed from two measurements, the intent is to determine this constant, *V*, that represents the transport of the elastic potential function and related parameters through the solid body.

4.4 This definition is based on the assumption that the medium that transmits the elastic waves is both homogeneous and isotropic. In such a case, a constant, *V*, is the applicable property throughout the whole volume and in all directions of the solid body. To the degree that this assumption holds, (Eq 1) and any other analytical description associated with other methods should yield a linear relationship between time of flight (or other parameters) and path length traversed. (Another form of this comparison would be for the computed sound speed to be a constant for different paths of different lengths.) Errors from this linear prediction are associated with errors in the measurement of time of flight (or the other parameters) and path length. Deviation of the measured values of sound speed beyond the estimated errors in the time measurement and the length measurement are connected with the systematic and random errors associated with all other unwanted variables of non-ideal material, non-ideal measuring technique, and lack of control on the many variables of indirect influence. An example of a second order dependence is a nonlinear relationship between time and distance due to diffraction effects associated with a finite transducer aperture.

4.5 In order to check a particular sound speed measuring system or particular applied technique, or both, a stepped gage block, similar to Fig. 1, of very uniform material properties can be constructed to check the performance of a measurement system by examining differences from the predicted linear relationship of Eq 1. Demonstrating that the calculated speed of sound, *V*, is constant for the different path lengths as determined in such a gage block experiment is a necessary condition for the confirmation of system performance to have a lack of bias. The described gage block has six path lengths, although a reference gage block for this purpose need not be limited to such a geometry. (Another geometry that is easier to manufacture is a rectangular parallelepiped with three distinctly different dimensions (**2**). Polyhedra of parallel opposite sides would also be appropriate.)



NOTE 1—Sound speed reference block manufactured of optical quality glass of high uniformity. The multiple sound propagation paths are marked L1 through L6.

FIG. 1 Sound Speed Reference Block, Optical Glass

4.6 Any gage block used for the purpose of checking the process of sound speed measurement must have uniform elastic and density characteristics throughout the gage block; thus, it must be homogeneous and isotropic. Only then can it be assumed that the speed of sound is uniform and not dependent on location and wave direction within the gage block. A method for assuring the high uniformity of the block is detailed.

5. Significance and Use

5.1 The use of sound speed values to determine changes in the elastic constants due to applied or residual stress requires that such measurements be of high precision and low bias. For that reason, special evaluation tests to determine a representative precision and bias for the specific technique, method, and equipment setup used are given.

5.2 Speed of sound is a measure that depends on the accurate measurements of length of path of travel and transit time or other related parameters such as frequency, etc. Both measurements are subject to certain interpretations and assumptions and are highly dependent on laboratory expertise. This practice provides a means of checking overall technique.

5.3 This practice shall be used when it is necessary to assess the systematic and random errors associated with a particular speed of sound measurement in a solid medium. It can be used to check both equipment performance and measurement technique for these errors. It can also be used to study inherent errors in a particular method. It can also be used to assess proposed corrections to sound speed measurements such as the phase corrections of Papadakis (**3**, **4**).

5.4 The resultant precision and bias determined by the use of the described block represents a more ideal situation than the same measurement performed in practice, in the field. Thus, the error for the specific field measurement may be larger than indicated by this test. This test represents the best error condition for a given technique and practice.

6. Procedure

6.1 *Speed of Sound Test Block Construction*:

6.1.1 Construct a glass block of the general shape and size of Fig. 1 of optical quality glass having at least a medium valued stress-optic coefficient (**5**). A stress-optic coefficient in the range of 20 to 40 nm/cm/MPa is desirable and the sample should be well annealed for a low internal stress state. Adhere to the glass manufacturer's annealing schedule. The dimensions of such a reference glass block can be chosen to approximate the dimensions and time of flight simulating the situation for which this assurance test is being done.

NOTE 1—The test block constructed and tested has nominal dimensions of L1 = 63.5 mm, L2 = 66.7 mm, L3 = 69.9 mm, L4 = 73 mm, L5 = 88.9

mm, and L6 = 101.6 mm. The step or facet on which the transducer is mounted should, of course, be at least as large as the aperture of the transducer.

6.1.2 The glass of this block shall be free of internal stresses and variations of optical index throughout its volume. Determine these two important features by examining the glass blank from which the block is to be cut between crossed polarizers before the cutting and polishing processes begin. Also, apply this test intermittently during both the grinding and polishing processes, and on the completed block. Any significant change in optical index or any significant internal stress patterns will show up immediately as a nonuniformity in the visual optical field. (A good quality optical glass that is well annealed and is uniform in temperature during observation will show no shadow or dark regions when viewed between crossed polaroids and the viewing regions will be perfectly uniform. Any region of shadow is an indication of optical birefringence associated with variations of uniformity of various physical parameters such as density, internal stress, and temperature.) Shadowed regions represent positions where the relative retardation differs by at least one-fifth of a wavelength of the illumination used. Such a visual indication should be grounds for rejection of the material blank.

6.1.3 Grind and polish all surfaces to better than 0.5 μm of being flat and each surface shall be cut so as to be parallel to the opposite surface.

6.1.4 Block thickness between parallel faces and along the direction of the propagation through this glass block must be measured to at least the accuracy appropriate to the desired results of the assurance test.

6.1.5 Thermal expansion for the test block should be known for length correction purposes and, if possible, low thermal expansion should be a factor in the choice of the material. Borosilicate crown glass is a good choice because it has a relatively low thermal expansion.

6.2 *Use of This Reference Block to Determine System and Method Performance for Sound Speed Measurements*:

6.2.1 Attach a sending/receiving transducer or transducers to the various faces of the reference gage block by the means intended for final use. This might include transducer holders, delay blocks, coupling materials of different thicknesses, and acoustic delay lines. Attempt to establish general ultrasonic conditions of the transducer attachment that closely duplicate the final conditions of use in practice.

6.2.2 The transducer should be located in the center of the face of the block used for each path length (see Fig. 1).

6.2.3 Measure a value of speed of sound for each path length through the reference block. The technique and method for measuring the time of flight being evaluated by this qualification test should be as near as possible to the technique and method that will be used in practice. (The same technique and method mean using the same transducer, attaching it in the same way, with the same delay line coupling if used, using the same transducer electrical driving equipment, using the same measuring electronics, making the timing coincidences in the same manner, maintaining the other independent variables in the same state of control, etc.) Accurately measure the various path lengths pertaining to the different dimensions of the block. Carry out a temperature measurement of the gage block for each ultrasonic measurement and record its value with the ultrasonic times of flight or phase shift. These temperature measurements should be to a precision of 0.1°C.

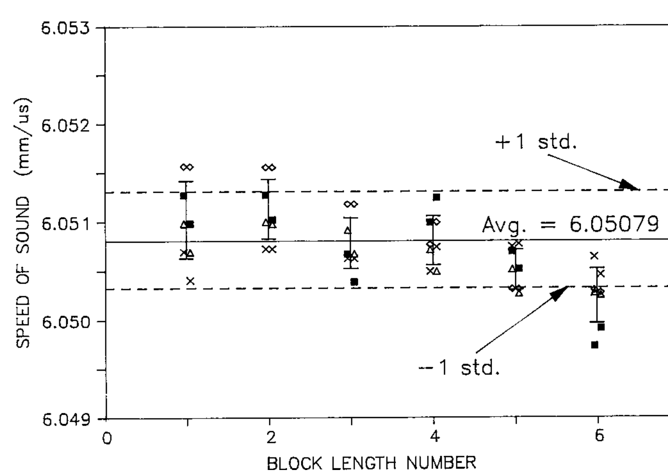
6.2.3.1 Thermally isolate the block from any external heating or cooling gradients such as local heating due to handling. Allow a period of 10 min to establish thermal equilibrium after any thermal disturbance has occurred.

6.2.4 Correct each sound speed value for thermal expansion and thermal changes in the elasticity associated with temperature variation occurring between measurements of the different path lengths of the set and then plot against the measured path length.

6.2.5 If poor precision or significant bias is suspected, measure and plot several values for each path length. This process will help establish a precision value for this particular arrangement and path length. In general, make at least five separate measurements of speed of sound for each path length to ascertain consistency of the process. From this set of measurements a standard deviation can be computed and error bounds assigned for each length.

6.2.6 The results for all path lengths can then be examined for the variation of the measured sound speed values from a single constant value. (The average value might be satisfactory for this purpose.)

6.2.7 Such a comparison is shown in Fig. 2. This figure demonstrates the ability to evaluate precision and bias from a set of measurements. See Appendix X1 for a more thorough description of this process. The solid line is the average for all the data, the dashed lines represent plus or minus one standard deviation (±1⁄12000) as computed from the total data set. Each data marker represents one measurement of the speed of sound. Each data set for a single length has an error ″window″ that is represented by a vertical“ I” bar. This error, “I”, is centered on the average for that length set and indicates plus and minus one



NOTE 1—Four different ultrasonic transducers were used and are indicated by different symbols. Two sets of values were taken for each transducer. “I” bars are estimated error limits for all the data of one path length as determined from the standard deviation of each set. The average value and the standard deviation of the total data set are shown.

FIG. 2 Results of Sound Speed Measurements on a Stepped Glass Reference Block