Designation: B646 – 17

Standard Practice for Fracture Toughness Testing of Aluminum Alloys[1]

This standard is issued under the fixed designation B646; 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.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope*

1.1 Fracture toughness is a key property for a number of aluminum alloys utilized in aerospace and process industries. Fracture toughness testing is often required for supplier qualification, quality control, and material release purposes. The purpose of this practice is to provide uniform test procedures for the industry, pointing out which current standards are utilized in specific cases, and providing guidelines where no standards exist. This practice provides guidance for testing *(a)* sheet and other products having a specified thickness less than 6.35 mm (0.250 in.), *(b)* intermediate thicknesses of plate, forgings, and extrusions that are too thin for valid plane-strain fracture toughness testing but too thick for treatment as sheet, such as products having a specified thickness greater than or equal to 6.35 mm (0.250 in.) but less than 25 to 50 mm (1 to 2 in.), depending on toughness level, and *(c)* relatively thick products where Test Method E399 is applicable.

1.2 This practice addresses both direct measurements of fracture toughness and screening tests, the latter recognizing the complexity and expense of making formal fracture toughness measurements on great quantities of production lots.

1.3 The values stated in SI units are to be regarded as the standard. The values in inch-pound units given in parenthesis are provided for information purposes only.

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.*

1.5 *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]

B557 Test Methods for Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products

B557M Test Methods for Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products (Metric)

B645 Practice for Linear-Elastic Plane–Strain Fracture Toughness Testing of Aluminum Alloys

E399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials

E561 Test Method for K_R Curve Determination

E1304 Test Method for Plane-Strain (Chevron-Notch) Fracture Toughness of Metallic Materials

E1823 Terminology Relating to Fatigue and Fracture Testing

3. Terminology

3.1 The terminology and definitions in the referenced documents, especially E1823, are applicable to this practice.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 For purposes of this practice, the following descriptions of terms are applicable in conjunction with Test Method E561:

3.2.2 *CMOD*—crack mouth opening displacement; the measurement of specimen displacement between two points spanning the machined notch at locations specific to the specimen being tested.

3.2.3 K_{R25}—a value of K_R on the K_R curve based on a 25 % secant intercept of the force-CMOD test record from a C(T) specimen and the effective crack size a_e at that point that otherwise satisfies the remaining-ligament criterion of Test Method E561. If the maximum force is reached prior to the 25 % secant intercept point, the maximum force point shall be used instead to determine the K_{R25} value.

[1] This practice is under the jurisdiction of ASTM Committee B07 on Light Metals and Alloys and is the direct responsibility of Subcommittee B07.05 on Testing.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

*A Summary of Changes section appears at the end of this standard

3.2.4 K_c—for the purpose of this practice, K_c is the critical stress intensity factor based on the maximum force value of the force-CMOD test record from an M(T) specimen and the effective crack size, a_e, at that point that otherwise satisfies the remaining-ligament criterion of Test Method E561.

3.2.5 K_{app} (also commonly designated K_{co})—the apparent plane stress fracture toughness based on the initial crack size, a_o, and the maximum force value of the force-CMOD test record from an M(T) specimen that otherwise satisfies the remaining-ligament criterion of Test Method E561.

4. Summary of Practice

4.1 This practice provides guidelines for the selection of tests to evaluate the fracture toughness properties of aluminum alloys, particularly for quality assurance and material release purposes. It also provides supplemental information regarding specimen size, analysis, and interpretation of results for the following products and test methods:

4.2 *Fracture Toughness Testing of Thin Products:*

4.2.1 K_R curve testing of M(T) middle-crack tension specimens in accordance with Test Method E561.

4.2.2 K_c and K_{app} (K_{co}) testing of M(T) specimens in general accordance with Test Method E561.

4.3 *Fracture Toughness Testing of Intermediate Thickness Products:*

4.3.1 Testing of C(T) compact-tension specimens in accordance with Test Method E399 supplemented with Practice B645.

4.3.2 Tests on C(T) specimens in accordance with Test Method E561 using the toughness parameter, K_{R25}.

4.4 *Fracture Toughness Testing of Thick Products:*

4.4.1 Linear-elastic plane-strain fracture testing in accordance with Test Method E399 supplemented with Practice B645.

5. Significance and Use

5.1 This practice is provided to develop and maintain uniformity in practices for the evaluation of the toughness of aluminum alloys, particularly with regard to supplier qualification, quality assurance, and material release to specifications.

5.2 It is emphasized that the use of these procedures will not alter the validity of data determined with specific test methods, but provides guidance in the interpretation of test results (valid or invalid) and guidance in the selection of a reasonable test procedure in those instances where no standard exists today.

6. Selection of Fracture Toughness Test Methods for Specific Products

6.1 Product size dictates the appropriate fracture toughness test method to be used for supplier qualification and periodic quality control testing. The fracture toughness measures and test methods are given below for the following product sizes:

6.2 *Thin Products*—For sheet and other products having specified thicknesses less than 6.35 mm (0.250 in.):

6.2.1 Determine the critical stress intensity factor (K_c) or the apparent fracture toughness (K_{app}) from M(T) specimens tested in general accordance with Test Method E561 as supplemented by this practice in 7.1; or

6.2.2 Determine the K_R curve measured from M(T) specimens tested in accordance with Test Method E561 as supplemented by this practice in 7.2.

6.3 *Thick Products*—For products sufficiently thick to obtain a valid linear-elastic plane-strain fracture toughness measurement, determine K_{Ic}, from C(T) specimens measured in accordance with Test Method E399 and supplemented by Practice B645 and by this practice in 7.3.

NOTE 1—The plane-strain chevron notch toughness K_{IvM} may be used as a direct quantitative measure of fracture toughness[3] when permitted by the material specification or by agreement between the purchaser and supplier. Testing and analysis of short-rod or short-bar specimens to obtain K_{IvM} shall be performed in accordance with Test Method E1304. Fracture toughness minimums for K_{IvM} should be established using the specimens and procedures of Test Method E1304 because those minimums may differ significantly from K_{Ic} minimums established using Test Method E399. The standard chevron notch specimens (short-rod or short-bar specimens 25.4 mm (1.00 in.) in diameter or width) are recommended. Two attractive features of the chevron notch test method are a) fatigue precracking is not required, and b) the specimen is small.

6.4 *Intermediate Thickness Products*—For products having thicknesses greater than or equal to 6.35 mm (0.250 in.), but too thin for valid linear-elastic plane-strain fracture toughness testing:

6.4.1 Determine K_Q from C(T) specimens tested in accordance with Test Method E399 supplemented with Practice B645 and this practice in 7.3; or

6.4.2 Determine K_{R25} from C(T) specimens tested in accordance with Test Method E561 as supplemented by this practice in 7.4.

6.5 *Thin Specimens from Thicker Products*—The methods of 6.2 may also be utilized on thin specimens machined from intermediate thickness or thick products for the purpose of evaluating their fracture toughness under plane stress conditions. These methods may be particularly desirable for products that will be machined into a thinner structural member. Typically, the specimen is machined from the product to a thickness representative of that used in the final application.

6.6 *Low Strength Alloy Products*—There are no current standard recommendations for toughness testing of relatively low-strength aluminum alloys which display large-scale yielding even in the presence of extremely large cracks in very thick sections. Such cases must be dealt with individually on a research basis using tests selected from program needs and anticipated design criteria. A typical case for general guidance is given in the literature.[4]

7. Fracture Toughness Testing Methods and Interpretation

7.1 *K_c and K_{app} (K_{co}) Testing*—Fracture toughness testing to obtain either the critical stress intensity (K_c) or the apparent

[3] Rolfe, S. T. and Novak, S. R., "Review of Developments in Plane Strain Fracture Toughness Testing," *ASTM STP 463*, ASTM, Sept. 1970, pp. 124–159.

[4] Kaufman, J. G., and Kelsey, R. A., "Fracture Toughness and Fatigue Properties of 5083-0 Plate and 5183 Welds for Liquefied Natural Gas Applications," *Properties of Materials for Liquefied Natural Gas Tankage, ASTM STP 579,* ASTM, 1975, pp. 138–158.

fracture toughness (K_{app}) shall be performed on M(T) specimens in accordance with Test Method E561 and the following supplemental requirements. K_{co} is another commonly used designation for the apparent fracture toughness, so all requirements for K_{app} testing are also applicable to K_{co}.

NOTE 2—K_c, K_{app}, and the K_R curve may all be obtained from the same test record and specimen. K_c or K_{app} are often preferred for quality assurance or material release purposes because they provide a single value measure of material fracture toughness that can be compared against a minimum specification value. For higher strength, lower toughness alloys where the maximum force is preceded by one or more unstable extensions of the crack, K_{app} is recommended for material release purposes.

7.1.1 The M(T) specimen width W and initial crack size a_o shall be in accordance with the material specification. The specimen thickness shall be the full thickness of the product for thin products less than or equal to 6.35 mm (0.250 in.) in thickness. The specimen shall be machined to a thickness of 6.35 mm (0.250 in.) by removing equal amounts from the top and bottom surfaces for thicker products, unless otherwise stated in the material specification. Recommended widths are W = 406 mm (16 in.) for medium strength, higher toughness products and W = 160 mm (6.3 in.) for high strength, lower toughness products. For very high toughness sheet alloys, W = 760 mm (30 in.) are also sometimes used for supplier qualification. The recommended initial crack size is $2a_o/W = 0.25$. In all cases the initial crack size $2a_o$ should be within the range of 0.25 to 0.40 W, inclusive, as allowed in Test Method E561. If no dimensional requirements are given in the material specification, the nominal specimen size shall be 406 mm (16 in.) wide, with 380 mm (15 in.) being an acceptable minimum width and the initial crack size shall be $2a_o/W = 0.25$. For all specimen widths and initial crack sizes, the tolerance for the initial crack size shall be +0.0125 W/- 0W or +2.5/-0 mm (+0.1/-0 in.), whichever is greater.

7.1.1.1 Tests for qualification and lot release testing shall be performed on specimens having the same width, or less, than specimens used for determining specification values.

NOTE 3—The values of K_c and K_{app} are dependent upon the interaction of the crack driving force, which is a function of specimen width, W, and the crack resistance curve (K_R curve). Thus, these values are dependent on specimen width (as well as thickness) and their values will typically decrease with decreasing specimen width, all other factors being equal. They also depend to a lesser extent on the initial crack size, a_o.

7.1.2 The M(T) specimen shall be machined and precracked in accordance with Test Method E561. The value of K_{max} in the fatigue precracking shall not exceed 16.5 MPa√m (15 ksi√in.). Fatigue precracking may be omitted only if it can be shown that doing so does not increase the measured value of K_c or K_{app}.

7.1.3 Except when specifically stated in the material specification, testing shall be performed with face stiffeners on the specimen to prevent buckling above or below the center slot.

7.1.4 The K_c value shall be calculated at the maximum force by the use of the secant equation for the M(T) specimen given in Test Method E561. The half crack size used in the K-expression shall be the effective half crack size, a_e, at the maximum force point calculated using the compliance expression for the M(T) specimens in Test Method E561. If, as sometimes happens, there is considerable crack extension at maximum force, the point at which the force first reaches the maximum shall be used in the crack size calculations.

7.1.5 The K_{app} value shall be calculated at the maximum force by the use of the secant equation for the M(T) specimen given in Test Method E561. The half crack size used in the K-expression shall be the initial crack size, a_o.

7.1.6 The net section validity of K_c or K_{app} shall be determined at the maximum force in accordance with Test Method E561.

7.1.7 Values of K_c or K_{app} calculated under conditions in which the net section stress exceeds 100 % of the tensile yield strength of the material are not suitable for design purposes and do not express the full toughness capability of the material, but they are useful for quality control or lot release; and as such a value of K_c or K_{app} that equals or exceeds a specified minimum value shall constitute evidence that the material passes the stated specification if the latter is based upon tests of the same or larger width of specimen.

7.2 *K_R Curve Testing*—Fracture toughness testing to obtain the K_R curve shall be performed on M(T) specimens in accordance with Test Method E561 and the following supplemental requirements.

NOTE 4—The K_R curve provides a complete measure of a material's resistance to slow-stable crack extension and consists of multiple data points (typically ten or more). When the K_R curve is used for material release purposes, the release criterion is typically based on minimum specified values of K_R at two or more values of effective crack extension, Δa_e. Use of the K_R curve for quality control purposes is suitable only for higher toughness alloys that exhibit stable crack extension and smoothly rising K_R curves. For higher strength, lower toughness alloys where the maximum force is preceded by one or more unstable extensions of the crack, use of K_{app} is recommended.

7.2.1 The specimen size, location, and testing requirements for K_c and K_{app} testing in 7.1.1, 7.1.2, and 7.1.3 shall also be used for K_R curve testing. For K_R curve testing, fatigue precracking is required unless it can be shown that omitting the precrack does not increase the measured values of K_R at the specified values of Δa_e.

NOTE 5—The K_R curve is a function of the material and specimen thickness, but is relatively independent of other geometric factors. However, the amount of valid K_R curve obtained (the maximum valid Δa_e) increases with specimen width W.

7.2.2 For the K_R curve, it is recommended that at least 20 sets of (K_R, Δa_e) pairs be determined from the test record of force versus CMOD in accordance with Test Method E561. At a minimum, (K_R, Δa_e) pairs shall be calculated using secant offsets having slope decrements of no more than five percent of the initial linear slope of the test record. The values of K_R corresponding to each secant offset shall be determined using the secant equation for the M(T) specimen in Test Method E561. The effective half crack size, a_e, used in the calculation of K_R and Δa_e for each secant offset, shall be determined using the compliance expression for M(T) panels in Test Method E561.

7.2.3 The net section validity shall be determined for each pair of K_R and Δa_e in accordance with Test Method E561. Those pairs meeting the validity requirement comprise the valid portion of the K_R curve. K_R values in the invalid region where net section yielding has occurred may be higher than valid points that would have been obtained with a larger specimen. However, provided the same specimen or smaller specimen size was used to establish the specification minimums, K_R values in the invalid region that equal or exceed a specified minimum shall constitute evidence that the material passes the stated specification.

7.2.4 Since minimum K_R values for material release purposes are typically specified at certain values of Δa_e, which do not necessarily coincide with those from the K_R curve analysis, linear interpolation between adjacent (K_R, Δa_e) pairs is acceptable as long as there is at least one (K_R, Δa_e) point between each specified value of Δa_e.

7.3 *Linear-elastic Plane-strain Fracture Toughness Testing*—Plain strain fracture toughness testing to obtain K_{Ic} or K_Q for material release purposes shall be performed on C(T) specimens in accordance with Test Method E399 and Practice B645. For any test result failing to meet the validity requirements for K_{Ic} in Method E399, the resulting K_Q value is usable for lot release, provided the requirements in Practice B645 are met. A K_Q meeting these requirements and which meets or exceeds the specified minimum value of K_{Ic} shall be considered as evidence that the lot meets the requirements of the material specification.

7.4 K_{R25} *Testing*—Fracture toughness testing to obtain the K_{R25} value shall be performed on C(T) specimens in accordance with Test Method E561 and the following supplemental requirements.

7.4.1 An evaluation of the material should be made to determine the optimum C(T) specimen geometry that will yield a valid K_{R25} result in accordance with Test Method E561. The optimum geometry (that is, width and initial crack size) will depend on the strength, toughness, and thickness of the material. The minimum recommended C(T) specimen width is W = 76.2 mm (3 in.), with a width of W = 102 mm (4 in.) or larger preferred. Once the optimum specimen geometry is established, the testing to establish the specification minimums and all future material release tests shall be made utilizing the same specimen geometry. The specimen thickness shall be the full product thickness unless otherwise stated in the material specification.

7.4.2 The C(T) specimen shall be machined and precracked in accordance with Test Method E561. The value of K_{max} in the fatigue precracking shall not exceed 16.5 MPa√m (15 ksi√in.).

7.4.3 The K_{R25} value shall be calculated at an evaluation point on the force-CMOD curve corresponding to either the 25 % secant offset point or the maximum force point, whichever occurs first in the test record. The 25 % secant offset is a line through the curve origin (as determined by the *x*-intercept of the initial linear slope of the test record) with a slope 75 % of the initial slope. The effective crack size, a_e, at the evaluation point shall be calculated using the secant slope from the curve origin to the evaluation point (either the 25 % secant offset point or the maximum force point, whichever occurs first) and the polynomial expression for crack size as a function of normalized compliance for the C(T) specimen given in Test Method E561. This value of a_e and the value of force at the evaluation point shall be used to calculate the K_{R25} value using the expression for K for the C(T) specimen given in Test Method E561.

7.4.4 The net section stress validity of the K_{R25} value shall be determined in accordance with Test Method E561. A value of K_{R25} that fails to meet the net section stress validity criteria of Test Method E561 but meets or exceeds the applicable specification value for K_{R25} shall be considered as evidence that the lot meets the requirements of the specification if the following conditions are met: *(a)* the test is made on a specimen of the same geometry as that used to determine the specification value, and *(b)* there is no evidence of specimen buckling during the test.

7.5 *Yield Strength for Validity Determination*—The preferred tensile yield strength for calculating the net section stress validity requirements in the above fracture toughness tests should be taken from the same test location and in the orientation corresponding with the direction of applied stress as the fracture toughness specimen. However, when this location does not coincide with the requirements for the tension test location in Test Methods B557 or B557M, or the material specification is different than Test Methods B557 or B557M, the yield strength from the specimen used for the tensile test may be used in the calculations. A conservative estimate of tensile yield strength, such as the specification minimum, can be used in the absence of measured tensile yield strengths.

8. Report

8.1 The test record shall include all information required by the applicable test method(s).

8.2 The complete test record is not normally required for material certification and lot release purposes. Such records are usually retained by the producer for future audits by the purchaser.

8.3 *Rounding*—For the purpose of determining conformance with a specified limit in a material or product specification, the value of the fracture toughness from the applicable test shall be rounded "to the nearest unit" in the last right hand significant digit used in expressing the limiting value in accordance with the rounding method of Practice E29. For a limit specified as a whole number, all digits shall be considered significant including zeros.

8.4 *Replacement Tests*—The test result from a fracture toughness test specimen may be discarded and a replacement test performed when: *(1)* the specimen was machined incorrectly, or *(2)* the test procedure was incorrect, or *(3)* the test machine malfunctioned.

8.5 *Retests of Fracture Toughness Tests*—Retests for fracture toughness tests in Section 7 shall be performed and interpreted in accordance with the applicable material specification or as otherwise agreed upon between the purchaser and supplier. If there is no specific provision for retests, and one or more test results fail to conform with the requirements of the material specification for reasons other than those in 8.4 after rounding in accordance with 8.3, the lot represented by that test result shall be subject to rejection, except as provided below:

8.5.1 For each specimen that failed, test at least two additional specimens at the specified test location from an area in the original sample adjacent to the failing specimen, or

8.5.2 For each specimen that failed, test an additional specimen at the specified location from at least two other samples.

8.5.3 If any retest fails, the lot shall be subject to rejection, except that the lot may be resubmitted for testing provided the producer has reworked the lot, as necessary, to correct the deficiencies.

9. Keywords

9.1 aluminum alloys; fracture toughness; linear-elastic; plane-strain; plane stress; quality assurance

SUMMARY OF CHANGES

Committee B07 has identified the location of selected changes to this standard since the last issue (B646 – 12) that may impact the use of this standard. (Approved Aug. 1, 2017.)

(1) Changed all occurrences of "original crack length" with "initial crack size" to maintain consistency with Test Method E561.
(2) Changed all occurrences of "K-R curve" to "K_R curve" to maintain consistency with Test Method E561.
(3) Changed all occurrences of "K_{fmax}" to "K_{max}" throughout the body of the standard.