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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 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.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

B557 Test Methods for Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products
B645 Practice for Linear-Elastic Plane–Strain Fracture Toughness Testing of Aluminum Alloys
E338 Test Method of Sharp-Notch Tension Testing of High-Strength Sheet Materials
E399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials
E561 Test Method for ***K-R*** Curve Determination
E602 Test Method for Sharp-Notch Tension Testing with Cylindrical Specimens
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 length 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.

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 length, 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 original crack length, a_o, and the maximum force value of the force-CMOD

[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.**

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 selection, 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 middle-crack tension M(T) 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 compact-tension C(T) 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, KR_{25}.

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.

4.5 *Screening Tests*:

4.5.1 Screening tests of thin products using sharply-edge-notched, sheet-type specimens in accordance with Test Method E338.

4.5.2 Screening tests of both intermediate and relatively thick products using the chevron notch (short-rod or short-bar) in accordance with Test Method E1304.

4.5.3 Screening tests of thick products using sharply-notched cylindrical specimens in accordance with Test Method E602.

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 Direct measures of fracture toughness are preferred over screening test methods and are highly recommended for supplier qualification and periodic quality control testing. The following measures of fracture toughness and test methods are recommended for these products:

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

6.2.1 The critical stress intensity factor (K_c) or the apparent fracture toughness (K_{app}) from an M(T) specimen and tested in general accordance with Test Method E561 as supplemented by this practice in 8.1.

6.2.2 The *K-R* curve measured from an M(T) specimen tested in accordance with Test Method E561 as supplemented by this practice in 8.2.

6.3 *Thick Products*—For products sufficiently thick to obtain a valid linear-elastic plane-strain fracture toughness measurement, K_{Ic}, from C(T) specimens measured in accordance with Test Method E399 supplemented by Practice B645 and by this practice in 8.3.

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 K_Q from C(T) specimens tested in accordance with Test Method E399 supplemented with Practice B645 and this practice in 8.3; or

6.4.2 K_{R25} from C(T) specimens tested in accordance with Test Method E561 as supplemented by this practice in 8.4.

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 which will be subsequently thinned by machining or other means. 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.[3]

7. Selection of Screening Test Methods for Specific Products

7.1 Screening tests are permitted for high volume, material release testing provided they are allowed by the material specification or by agreement between the purchaser and supplier. The following screening test methods are recommended for these products:

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

7.2.1 Tension tests of sharply-edge-notched, sheet-type specimens in accordance with Test Method E338 as supplemented by this practice in 9.1 and 9.2, and the corresponding correlations of such data with the critical stress-intensity factors (K_c) determined in accordance with this practice are recommended.

[3] 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.

7.3 *Thick Products*—For products sufficiently thick to obtain a valid linear-elastic plane-strain fracture toughness measurement:

7.3.1 Tension tests of sharply-notched, cylindrical specimens in accordance with Test Method E602 as supplemented by this practice in 9.1 and 9.3 and the associated correlation with linear-elastic plane-strain fracture toughness, K_{Ic}, as determined in accordance with Test Method E399 and Practice B645 are recommended. In addition, the following recommended alternative screening tests may be applied:

7.3.2 The chevron notch (short-rod and short-bar) test described in Test Method E1304 as supplemented by this practice in 9.1 and 9.4.

7.4 *Intermediate Thickness Products*—For products having specified thicknesses greater than or equal to 6.35 mm (0.250 in.), but too thin for valid plane-strain fracture toughness testing, there is insufficient data to justify strong recommendations for screening test procedures. Presumably, correlation with fracture toughness indices could be made with the results of tests using either chevron-notch (short-rod or short-bar) specimens, sharp-edge-notched, sheet-type specimens, sharply-notched, cylindrical specimens or sharp-notch Charpy specimens.

8. Fracture Toughness Testing Methods and Interpretation

8.1 *K_c and K_{app} (K_{co}) Testing*—Fracture toughness testing to obtain either the critical stress intensity (K_c) or the apparent 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 1—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.

8.1.1 The M(T) specimen width *W* and original crack length 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 original crack size is $2a_o/W = 0.25$. In all cases the original 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 original crack size shall be $2a_o/W = 0.25$. For all specimen widths and original crack sizes, the tolerance for the original crack size shall be +0.0125*W*/- 0*W* or +2.5/-0 mm (+0.1/-0 in.), whichever is greater.

8.1.1.1 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 2—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 original crack length, a_o.

8.1.2 The M(T) specimen shall be machined and precracked in accordance with Test Method E561. The value of K_{fmax} in the fatigue precracking shall not exceed 16.5 MPa$\sqrt{m}$ (15 ksi$\sqrt{in.}$). 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}.

8.1.3 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.

8.1.4 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 length used in the *K*-expression shall be the effective half crack length, 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 length calculations.

8.1.5 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 length used in the *K*-expression shall be the original crack length, a_o.

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

8.1.7 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 such 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.

8.2 *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 3—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