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Standard Practice for Fracture Toughness Testing of Aluminum Alloys¹

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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) thin products, of thicknesses equivalent to sheet that is ≤ 0.249 in. (≤ 6.32 mm), (b) intermediate thicknesses of plate, forgings, and extrusions, too thin for valid plane-strain fracture toughness testing but too thick for treatment as sheet, for example, over 0.249 in. (6.32 mm) and up to 1 to 2 in. (25 to 50 mm), dependent upon toughness level, and (c) relatively thick products where Test Method E 399 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 inch-pound units are to be regarded as the standard. The values in SI 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

B 557 Test Methods of Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products

B 645 Practice for Plane-Strain Fracture Toughness Testing of Aluminum Alloys

E 23 Test Methods for Notched Bar Impact Testing of Metallic Materials

E 338 Test Method of Sharp-Notch Tension Testing of High-Strength Sheet Materials

E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials

E 561 Practice for R-Curve Determination

E 602 Test Method for Sharp-Notch Tension Testing with Cylindrical Specimens

E 1304 Test Method for Plane-Strain (Chevron Notch) Fracture Toughness of Metallic Materials

E 1823 Terminology Relating to Fatigue and Fracture Testing

3. Terminology

3.1 The terminology and definitions in the referenced documents 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 E 561 and use of the compact specimen:

3.2.2 K_{R25} —a value of K_R on the R-curve based on a 25 % secant intercept of the force-crack opening displacement 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 E 561.

3.2.3 K_{Rmax} —a value of K_R on the R-curve based on the maximum force value of the force-crack opening displacement 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 E 561. The K_{Rmax} value is used when the 25 % secant intercept occurs at a point after the maximum force is reached.

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-crack opening displacement 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 E 561.

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.

3.2.5 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-crack opening displacement test record from an M(T) specimen that otherwise satisfies the remaining-ligament criterion of Test Method E 561.

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 R-Curve testing of middle-crack tension, M(T), specimens in accordance with Test Method E 561.

4.2.2 K_c and K_{app} (K_{co}) testing of M(T) specimens in general accordance with Test Method E 561.

4.3 Fracture Toughness Testing of Intermediate Thickness Products:

4.3.1 Testing of compact-tension, C(T), specimens in accordance with Test Method E 399 supplemented with Practice B 645.

4.3.2 Tests on C(T) specimens in accordance with Test Method E 561 using the toughness parameter, KR_{25} .

4.4 Fracture Toughness Testing of Thick Products:

4.4.1 Plane-strain fracture testing in accordance with Test Method E 399 supplemented with Practice B 645.

4.5 Screening Tests:

4.5.1 Screening tests of thin products using sharply-edge-notched, sheet-type specimens in accordance with Test Method E 338.

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 E 1304.

4.5.3 Screening tests for a range of thicknesses from about 0.1 in. (2.54 mm) upward using the sharp-notch Charpy test as covered in Test Methods E 23.

4.5.4 Screening tests of thick products using sharply-notched cylindrical specimens in accordance with Test Method E 602.

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 a thickness less than 0.250 in. (6.35 mm):

6.2.1 The critical stress intensity factor (K_c) or the apparent fracture toughness (K_{app}) from a middle-cracked tension, M(T), specimen and tested in general accordance with Test Method E 561 as supplemented by this practice in 8.1.

6.2.2 The R-curve measured from a middle-cracked tension, M(T), specimen tested in accordance with Test Method E 561 as supplemented by this practice in 8.2.

6.3 *Thick Products*—For products sufficiently thick to obtain a valid plane strain fracture toughness measurement, K_{Ic} , from C(T) specimens measured in accordance with Test Method E 399 supplemented by Practice B 645 and by this practice in 8.3.

6.4 *Intermediate Thickness Products*—For products having a thickness ≥ 0.250 in. (≥ 6.35 mm), but too thin for valid plane-strain fracture toughness testing:

6.4.1 K_Q from compact-tension, C(T), specimens tested in accordance with Test Method E 399 supplemented with Practice B 645 and this practice in 8.3; or

6.4.2 KR_{25} from a compact-tension, C(T) specimen tested in accordance with Test Method E 561 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 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 thickness less than 0.250 in. (6.35 mm):

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.

7.2.1 Tension tests of sharply-edge-notched, sheet-type specimens in accordance with Test Method E 338 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.

7.2.2 The sharp-notch Charpy screening test in accordance with Test Methods E 23 as supplemented by this practice in 9.1 and 9.3 may also be applied for correlative purposes for products 0.10 in. (2.54 mm) and thicker.

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

7.3.1 Tension tests of sharply-notched, cylindrical specimens in accordance with Test Method E 602 as supplemented by this practice in 9.1 and 9.4 and the associated correlation with plane-strain fracture toughness, K_{Ic} , as determined in accordance with Test Method E 399 and Practice B 645 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 E 1304 as supplemented by this practice in 9.1 and 9.5.

7.3.3 The sharp-notch Charpy screening test in accordance with Test Methods E 23 as supplemented by this practice in 9.1 and 9.3.

7.4 *Intermediate Thickness Products*—For products having a thickness ≥ 0.250 in. (≥ 6.35 mm), 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 E 561 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 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 and the specimen thickness shall be the full thickness of the product for thin products ≤ 0.250 in. (≤ 6.35 mm) in thickness and 0.250 in. (6.35 mm) for thicker products, unless otherwise stated in the material specification. Specimens not of full product thickness shall be excised from the mid-plane of the product unless otherwise stated in the material specifica-

tion. Recommended widths are $W = 16$ in. (406 mm) for medium strength, higher toughness products and $W = 6.3$ in. (160 mm) for high strength, lower toughness products. For very high toughness sheet alloys, $W = 30$ in. (760 mm) are also sometimes used for supplier qualification. The recommended original crack size is one quarter of the width, W ; that is $2a_o/W = 0.25$. In all cases the original crack size, a_o , should be within the range of 0.25 to $0.40W$, inclusive, allowed in Test Method E 561. If no dimensional requirements are given in the material specification, the nominal specimen size shall be 16 in. (405 mm) wide, with 15 in. (380 mm) being an acceptable minimum width and the initial crack length, $2a_o$, shall be equal to one quarter of the width, W ; that is, $2a_o/W = 0.25$. For all specimen widths and original crack sizes, the tolerance for the original crack size shall be $+0.0125W - 0W$ or $+0.1/-0$ in. ($+2.5/-0$ mm), whichever is greater.

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 (R-curve). Thus, they are specimen width (as well as thickness) dependent 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 . Therefore, both the specified value and qualification or lot release testing should be based on specimens having the same width and original crack length.

8.1.2 The M(T) specimen shall be machined and precracked in accordance with Test Method E 561. The value of K_{fmax} in the fatigue precracking shall not exceed 15 ksi $\sqrt{\text{in}}$. (16.5 MPa $\sqrt{\text{m}}$). 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 M(T) specimen given in Test Method E 561. 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 M(T) panels in Test Method E 561. 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 E 561. 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 E 561.

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.