Designation: B909 – 17

Standard Guide for Plane Strain Fracture Toughness Testing of Non-Stress Relieved Aluminum Products[1]

This standard is issued under the fixed designation B909; 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.

1. Scope

1.1 This guide covers supplementary guidelines for plane-strain fracture toughness testing of aluminum products for which complete stress relief is not practicable. Guidelines for recognizing when residual stresses may be significantly biasing test results are presented, as well as methods for minimizing the effects of residual stress during testing. This guide also provides guidelines for correction and interpretation of data produced during the testing of these products. Test Method E399 is the standard test method to be used for plane-strain fracture toughness testing of aluminum alloys.

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.*

1.3 *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]

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

E561 Test Method for K_R Curve Determination

E1823 Terminology Relating to Fatigue and Fracture Testing

2.2 *ANSI Standard:*

ANSI H35.1 Alloy and Temper Designations for Aluminum[3]

2.3 *ISO Standard:*

ISO 12737 Metallic Materials–Determination of Plane Strain Fracture Toughness[4]

3. Terminology

3.1 *Definitions*—Terminology in Test Method E399 and Terminology E1823 are applicable herein.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *corrected plane-strain fracture toughness*— a test result, designated K_Q (corrected), which has been corrected for residual stress bias by one of the methods outlined in this guide.

3.2.1.1 *Discussion*—The corrected result is an estimation of the K_Q or K_{Ic} that would have been obtained in a residual stress free specimen. The corrected result may be obtained from a test record which yielded either an invalid K_Q or valid K_{Ic}, but for which there is evidence that significant residual stress is present in the test coupon.

3.2.2 *invalid plane-strain fracture toughness*— a test result, designated K_Q, that does not meet one or more validity requirements in Test Method E399 or ISO 12737 and may or may not be significantly influenced by residual stress.

3.2.3 *valid plane-strain fracture toughness*— a test result, designated K_{Ic}, meeting the validity requirements in Test Method E399 or ISO 12737 that may or may not be significantly influenced by residual stress.

4. Significance and Use

4.1 The property K_{Ic}, determined by Test Method E399 or ISO 12737, characterizes a material's resistance to fracture in a neutral environment and in the presence of a sharp crack subjected to an applied opening force or moment within a field of high constraint to lateral plastic flow (plane strain condition). A K_{Ic} value is considered to be a lower limiting value of fracture toughness associated with the plane strain state.

4.1.1 Thermal quenching processes used with precipitation hardened aluminum alloy products can introduce significant

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

Current edition approved May 1, 2017. Published June 2017. Originally approved in 2000. Last previous edition approved in 2011 as B909 – 00 (2011). DOI: 10.1520/B0909-17.

[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] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[4] Available from International Organization for Standardization (ISO), 1 rue de Varembé, Case postale 56, CH-1211, Geneva 20, Switzerland, http://www.iso.ch.

residual stresses in the product. Mechanical stress relief procedures (stretching, compression) are commonly used to relieve these residual stresses in products with simple shapes. However, in the case of mill products with thick cross-sections (for example, heavy gage plate or large hand forgings) or complex shapes (for example, closed die forgings, complex open die forgings, stepped extrusions, castings), complete mechanical stress relief is not always possible. In other instances residual stresses may be unintentionally introduced into a product during fabrication operations such as straightening, forming, or welding operations.

4.1.2 Specimens taken from such products that contain residual stress will likewise themselves contain residual stress. While the act of specimen extraction in itself partially relieves and redistributes the pattern of original stress, the remaining magnitude can still be appreciable enough to cause significant error in the ensuing test result.

4.1.3 Residual stress is superimposed on the applied stress and results in an actual crack-tip stress intensity that is different from that based solely on externally applied forces or displacements.

4.1.4 Tests that utilize deep edge-notched specimens such as the compact tension C(T) are particularly sensitive to distortion during specimen machining when influential residual stress is present. In general, for those cases where such residual stresses are thermal quench induced, the resulting K_{Ic} or K_Q result is typically biased upward (that is, K_Q is higher than that which would have been achieved in a residual stress free specimen). The inflated values result from the combination of specimen distortion and bending moments caused by the redistribution of residual stress during specimen machining and excessive fatigue precrack from curvature[5].

4.2 This guide can serve the following purposes:

4.2.1 Provide warning signs that the measured value of K_{Ic} has been biased by residual stresses and may not be a lower limit value of fracture toughness.

4.2.2 Provide experimental methods by which to minimize the effect of residual stress on measured fracture toughness values.

4.2.3 Suggest methods that can be used to correct residual stress influenced values of fracture toughness to values that approximate a fracture toughness value representative of a test performed without residual stress bias.

5. Interferences

5.1 There are a number of warning signs that test measurements are or might be biased by the presence of residual stress. If any one or more of the following conditions exist, residual stress bias of the ensuing plane strain fracture toughness test result should be suspected. The likelihood that residual stresses are biasing test results increases as the number of warning signs increase.

5.1.1 A temper designation of a heat treatable aluminum product that does not indicate that it was stress relieved. Stress relief is indicated by any of the following temper designations: T_51, T_510, T_511, T_52, or T_54, as described in ANSI H35.1.

5.1.2 Machining distortion during specimen preparation. An effective method to quantify distortion of a C(T) specimen is to measure the specimen height directly above the knife edges (typically at the front face for specimen designs with integral knife edges) prior to and after machining the notch. Experience has shown that for an aluminum C(T) specimen with a notch length to width ratio (a_o/W) of 0.45, a difference in the height measured before and after machining the notch equal to or greater than 0.003 in. (0.076 mm) is an indicator that the ensuing test result will be significantly influenced by residual stress.

5.1.3 Excessive fatigue precrack front curvature not meeting the crack-front straightness requirements in Test Method E399 or ISO 12737.

5.1.4 Unusually high loads or number of cycles required for precracking relative to the same or similar alloy/products.

5.1.5 A significant change in fracture toughness that is greater than that typically observed upon changing specimen configuration (for example, from C(T) to three point bend bar) or upon changing specimen's *W* dimension that cannot be explained by other means. For example, if residual stress is biasing fracture toughness tests results, then increasing the specimen's *W* dimension typically results in increasing K_Q values.

NOTE 1—Other factors, such as a steeply rising R-curve (Practice E561) in high toughness alloy/products, may also be responsible for K_Q values increasing with increasing specimen *W* dimension.

5.1.6 A nonlinear load-COD trace during the initial elastic portion of the test record. This result is indicative of the residual stress clamping that is being overcome to open the crack under the progressively increasing applied load.

6. Minimizing Effects of Residual Stress on Fracture Toughness Measurements

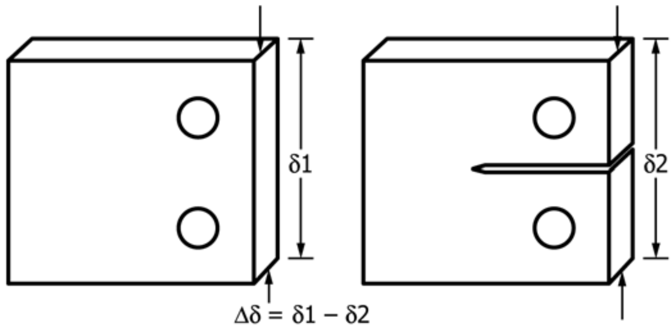
6.1 When testing aluminum products that have not been stress relieved, there are two approaches available to minimize or eliminate the effects of residual stress on fracture toughness measurements. The first approach involves the use of one or more experimental methods designed to minimize the residual stress in test specimens. The second approach involves the use of post-test correction methods to estimate the fracture toughness K_Q or K_{Ic} that would have been obtained had the test specimen been free of residual stress.

7. Experimental Methods to Minimize Effects of Residual Stress

7.1 The following considerations can be used to minimize the magnitude of residual stress in test specimens.

7.1.1 To minimize the biasing influences of both distortion-induced clamping (or opening) moments and precrack front curvature, the specimen thickness (*B*) should be as small as possible with respect to the host product thickness, while maintaining a specimen *W/B* ratio of 2. However, this must be done such that the specimen B and W dimensions are large

[5] Bucci, R.J., "Effect of Residual Stress on Fatigue Crack Growth Rate Measurement," Fracture Mechanics: Thirteenth Conference, *ASTM STP 743*, American Society for Testing and Materials, 1981, pp. 28–47.



NOTE 1—Measure the specimen height before and after machining the crack starter notch.

FIG. 1 Residual Stress Correction Practice for K_{Ic} Testing of C(T) Specimens

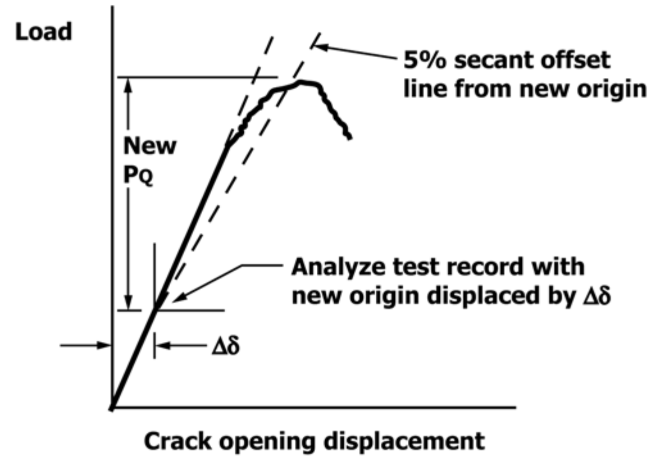


FIG. 2 K_{Ic} Test Residual Stress Correction Schematic

enough to meet the Test Method E399 or ISO 12737 specimen size requirements for valid K_{Ic} measurement.

7.1.2 In cases where the specimen size required to obtain a valid K_{Ic} is too large for the strategy described in 7.1.1 to be effective, the use of special precracking techniques can produce a straighter fatigue precrack and reduce the residual stress bias. One such technique involves the use of high stress ratios for precracking. Experience has shown that precracking at a cyclic stress ratio of 0.7 results in significantly straighter crack fronts than precracks produced at a stress ratio of 0.1. Moreover, the straighter crack fronts that result from precracking at higher R-ratio have been shown to reduce the error in the ensuing fracture toughness measurement by up to 75 %.

NOTE 2—Test Method E399 requires precracking to be performed at stress ratios between –1 and 0.1 (inclusive). Therefore, specimens precracked at stress ratios greater than 0.1 and less than or equal to 0.7 will result in K_Q, which are invalid in accordance with Test Method E399. However, even though invalid, the K_Q obtained from a specimen precracked at higher stress ratios but meeting the crack front straightness requirements and other validity requirements in Test Method E399 should be a significantly better estimate of the plane-strain fracture toughness, K_{Ic}, than an invalid K_Q obtained from a specimen precracked at a stress ratio meeting Test Method E399 requirements but with excessive crack front curvature.

7.1.3 Measurement of the specimen height change, as depicted in Fig. 1, can be used as a gage of the severity of the bending moment induced residual stress bias. The measurements can also be used as a method to estimate the "true" fracture toughness through a post-test correction described in Section 8.

8. Post-Test Residual Stress Correction Methods

8.1 *Method 1*—This correction method utilizes the specimen height change measurement described in Fig. 1 and denoted as $\Delta\delta$. As shown in Fig. 2, the origin of the residual stress biased load-displacement test record is modified by displacing the origin by an amount equal to $\Delta\delta$ and to the load associated with that displacement. The test is now analyzed using this new origin and modified load-displacement record with the standard methodology described in Test Method E399.

NOTE 3—Limited experimental evidence[6,7] indicates that under precracking conditions resulting in excessive crack front curvature (that is, not meeting the crack front straightness requirements in Test Method E399), K_Q (corrected) values obtained by Method 1 are within 15 % of the K_{Ic} or K_Q value that would have been obtained in a residual stress free specimen. Limited experimental evidence also indicates that the accuracy of the correction method decreases when the specimen has been precracked at higher stress ratios, such as 0.7, to obtain a straighter crack front. In this case, Method 2 is preferred.

8.2 *Method 2*—A second empirical residual correction method involves the use of a modified fatigue precrack length in the calculation of K_Q. For this correction method, the fatigue precrack length is calculated as the average of the two specimen surface precrack lengths. The K_Q value is then calculated using the standard fracture mechanics equations for the C(T) specimen. Empirical evidence indicates that this method has greater accuracy than that described in 8.1 when the specimen has been precracked at higher stress ratios, such as 0.7.

NOTE 4—Limited experimental evidence[8] indicates that K_Q (corrected) values obtained by Method 2 are within 10 % of the K_{Ic} or K_Q that would have been obtained in a residual stress free specimen, regardless of the crack front straightness for a typical residual stress distribution produced by quenching, which is compression at the surface and tension at the center of the specimen. For this typical distribution, the two surface precrack lengths will be smaller than those in the center of the specimen. For non-typical distributions where the residual stresses are in compression at the center and tension at the surface, this method may not be applicable.

NOTE 5—A K_Q (corrected) value derived from a valid K_{Ic} or an invalid K_Q that is invalid only due to failure to meet the crack front straightness requirements and fatigue precracking stress ratio requirements of Test Method E399 or ISO 12737 is an estimate of the plane-strain fracture

[6] Bucci, R.J. and Bush, R.W., "Purging Residual Stress Effects from Fracture Property Measurements," Minutes for the 94th MIL-HDBK-5 Coordination Meeting held in Williamsburg, VA, October 14–15, 1997, Wright Laboratories, Wright Patterson Air Force Base, Nov 14, 1997.

[7] Bucci, R.J., Bush, R.W., and Kuhlman, G.W., "Damage Tolerance Characterization of Thick, Wrought Aluminum Products with and without Stress Relief: Focus on Toughness and Crack Growth Characteristics to Capture Advances in Forging Stress Relief Technology," Proceedings, 1997 USAF Aircraft Structural Integrity Program Conference, San Antonio, TX, December 2–4, 1997.

[8] Bush, R.W. and Mahler, M.H., "Residual Stress and Fracture Toughness Measurements–Quantification of the Measurement Errors and Applicability of Various Correction Methodologies," Alcoa Letter Report, Dec. 29, 1997.

toughness, K_{Ic}, that would have been obtained in a residual stress free specimen (see also Note 2). A K_Q (corrected) value derived from a K_Q value, which is invalid due to failure to meet other validity requirements such as requirements on thickness B or P_{max}/P_Q is an estimate of the K_Q value that would have been obtained in a residual stress free specimen. Under these conditions, K_Q (corrected) may not represent or approximate K_{Ic}.

9. Report

9.1 The report for plane-strain toughness test results that are suspected of having been influenced by residual stresses shall note that suspicion and the reasons it is suspected.

9.2 If the fracture toughness value has been corrected after the test, both the uncorrected value of K_Q or K_{Ic} and corrected fracture toughness value K_Q (corrected) shall be reported. The method used (Method 1 or Method 2) to correct the fracture toughness value and any measurements used in the correction process shall be reported.

10. Keywords

10.1 aluminum; aluminum alloys; aluminum products; fracture toughness; residual stress