Designation: B909 – 21

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 an empirical correction as well as 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, health, and environmental 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 of Metallic Materials

E561 Test Method for K_R Curve Determination

E1823 Terminology Relating to Fatigue and Fracture Testing

2.2 *ANSI Standard:*[3]

ANSI H35.1 Alloy and Temper Designations for Aluminum

2.3 *ISO Standard:*[4]

ISO 12135 Unified method of test for the determination of quasistatic fracture toughness

3. Terminology

3.1 *Definitions:*

3.1.1 Terms 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 12135 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 12135 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 12135, 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, 2021. Published June 2021. Originally approved in 2000. Last previous edition approved in 2017 as B909 – 17. DOI: 10.1520/B0909-21.

[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), ISO Central Secretariat, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, https://www.iso.org.

residual stresses into the product.[5] 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 gauge 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.

NOTE 1—For the purposes of this guide, only bulk residual stress is considered (that is, of the type typically created during a quench process for thermal heat treatment) and not engineered residual stress, such as from shot peening or cold hole expansion.

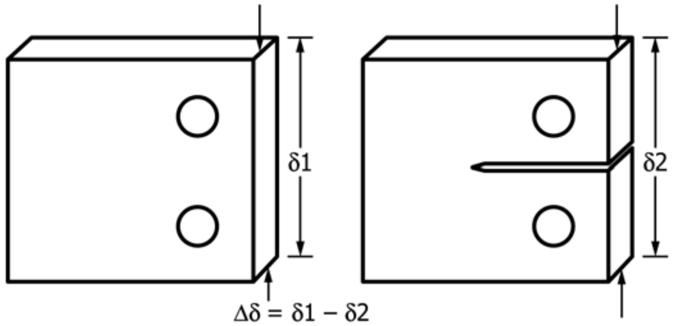
4.1.2 Specimens taken from such products that contain residual stress will likewise themselves contain residual stress. While the act of specimen extraction in itself partially relieves and redistributes the pattern of original stress, the remaining magnitude can still be appreciable enough to cause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

4.1.3 Residual stress is a non-proportional internal stress that is superimposed on the applied stress and results in an actual crack-tip stress-intensity factor that is different from one based solely on externally applied forces or displacements, and residual stress can bias the toughness measurement. Conceptually, compressive residual stress in the region of the crack tip must be overcome by the applied force before the crack tip experiences tensile stresses, thus biasing the K_Q or K_{Ic} measurement to a higher value, potentially producing a non-lower-bound toughness value. Quantitatively, the effect depends on stress equilibrium for the continuously varying residual stress field and the associated crack tip response. Conversely, a tensile residual stress is additive to the applied force and biases the measured K_Q or K_{ic} result to a lower value, potentially under-representing the material "true" toughness capability.

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 substantial 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 redistribution of residual stress during specimen machining and excessive fatigue pre-crack front curvature caused by variable residual stresses across the crack front.[6]

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.



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

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

4.2.2 Provide experimental methods that can be used 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 characterize 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 (see Fig. 1). 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 (for example, for a specimen size of nominally W = 2 or 3 in. (50 or 75 mm) with W/B = 2).

NOTE 2—Often the first indication of residual stresses is when there is difficulty sawing the specimen notch due to excessive drag on the sawblade. This is caused by the release of compressive residual stresses at the front face causing the specimen to clamp down on the sawblade, which creates excessive vibration and noise. Incremental sawing, where the sawblade is backed out periodically, is usually the solution to this problem.

5.1.3 Excessive fatigue precrack front curvature not meeting the crack-front straightness requirements in Test Method E399 or ISO 12135.

---

[5] Prime, M. B. and Hill, M. R., "Residual stress, stress relief, and inhomogeneity in aluminum plate," *Scripta Materialia*, 46, 2002, pp. 77–82.

[6] 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.

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 may result in increasing K_Q values because the larger specimen will intersect a larger portion of the stress field in the host material.

NOTE 3—Other factors, such as a steeply rising R-curve (see Type I force-displacement (CMOD) record in Test Method E399) in high toughness alloy/products, may also be responsible for K_Q values increasing with increasing specimen *W* dimension. See also Test Method E561.

5.1.6 A nonlinear load-COD trace during the initial elastic portion of the test record. This result is indicative of residual stress having caused crack closure in the precrack that must be overcome to open the crack under the progressively increasing applied load. This closure can cause nonlinearity in the test record that can affect the K_Q and K_{Ic} value determinations. The nonlinearity should be ignored when determining the linear region of the force-CMOD curve. Slight initial nonlinearity of the test record is frequently observed and is also to be ignored.

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. Research methods are also available to measure the effect of residual stress on the resulting K_Q value from a fracture toughness test.

7. Experimental Methods to Assess and 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 residual stress and precrack front curvature, minimize the specimen dimensions to the extent possible. The specimen thickness (*B*) should be as small as possible with respect to the host product thickness, while maintaining specimen proportions within the range $2 \leq W/B \leq 4$ in accordance with Test Method E399 requirements. However, this must be done such that the specimen B and W dimensions are large enough to meet the Test Method E399 or ISO 12135 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 stress ratios have been shown to reduce the error in the ensuing fracture toughness measurement by up to 75 %.

NOTE 4—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 criterion for the severity of the residual stress bias. Note that the notch height as indicated in Fig. 1 may be useful as a subjective indicator of residual stress, not a quantitative indicator. Subsection 8.2 describes two approaches to quantitatively characterize the effects of residual stress on the crack driving force for a K_{Ic} specimen.

7.1.4 In those cases where the potential for bulk residual stress bias is suspected, it is recommended that samples be isolated from two or more distinct locations that are suspected of differing bulk residual stress profiles within the host material.

NOTE 5—Other factors than residual stress can affect variation in fracture toughness as a function of position in the host material, such as variation in grain structure or microstructure as a function of position.

8. Post-Test Residual Stress Correction Methods

8.1 An empirical correction method[7] has been evaluated for cases where crack tunneling (more crack growth at the center of the specimen than the surface) has occurred during precrack beyond what is allowed by Test Method E399. Often crack tunneling is caused by through-thickness residual stress induced by the quench process for aluminum alloys that have incomplete or no stress-relief.[8] The empirical 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.

NOTE 6—Limited experimental evidence[9] indicates that K_Q (corrected) values obtained by this test method 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

---

[7] 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.

[8] Prime, M. B., DeWald, A. T., Hill, M. R., Clausen, B., and Tran, M., "Forensic determination of residual stresses and KI from fracture surface mismatch," *Engineering Fracture Mechanics*, Vol 116, 2014, pp. 158–171.

[9] 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.