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

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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 E 399 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.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 399 Test Method for Plane-Strain Fracture Toughness Testing of Metallic Materials[2]
E 561 Practice for R-Curve Determination[2]
E 1823 Terminology Relating to Fatigue and Fracture Testing[2]

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 E 399 and Terminology E 1823 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. 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 E 399 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 E 399 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 E 399 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 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

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[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.

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[2] *Annual Book of ASTM Standards*, Vol 03.01.

[3] Available from American National Standards Institute (ANSI), 11 W. 42nd St., New York, NY 10036.

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

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. Warning Signs

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 E 399 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 plan size that cannot be explained by other means. For example, if residual stress is biasing fracture toughness tests results, then increasing the specimen plan size typically results in increasing K_q values.

NOTE 1—Other factors, such as a steeply rising R-curve (Practice E 561) in high toughness alloy/products, may also be responsible for K_q values increasing with increasing specimen plan size.

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 enough to meet the Test Method E 399 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 E 399 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

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[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.