



Designation: E3459 – 24

Standard Guide for In-Plane Biaxial Testing with Cruciform Type Specimens¹

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1. Scope

1.1 The purpose of this standard is to serve as a guide for testing and characterization of homogeneous metallic materials using cruciform type specimens subjected to in-plane biaxial loading conditions at isothermal, ambient or elevated temperatures. Test conditions covered by this standard guide include biaxial deformation and strength (under combined tension/compression), fatigue crack initiation and fatigue crack growth under cyclic, biaxial loading conditions.

1.2 *Units*—The values stated in SI units are to be regarded as the standard. No other units of measurement are included in this standard.

1.3 *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.*

1.4 *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

- E3 Guide for Preparation of Metallographic Specimens
- E4 Practices for Force Calibration and Verification of Testing Machines
- E6 Terminology Relating to Methods of Mechanical Testing
- E8/E8M Test Methods for Tension Testing of Metallic Materials
- E9 Test Methods of Compression Testing of Metallic Materials at Room Temperature

¹ This guide is under the jurisdiction of ASTM Committee E08 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.05 on Cyclic Deformation and Fatigue Crack Formation.

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² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at www.astm.org/contact. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

- E83 Practice for Verification and Classification of Extensometer Systems
- E112 Test Methods for Determining Average Grain Size
- E209 Practice for Compression Tests of Metallic Materials at Elevated Temperatures with Conventional or Rapid Heating Rates and Strain Rates
- E466 Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials
- E467 Practice for Verification of Constant Amplitude Dynamic Forces in an Axial Fatigue Testing System
- E606/E606M Test Method for Strain-Controlled Fatigue Testing
- E647 Test Method for Measurement of Fatigue Crack Growth Rates
- E1012 Practice for Verification of Testing Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application
- E1823 Terminology Relating to Fatigue and Fracture Testing
- E2207 Practice for Strain-Controlled Axial-Torsional Fatigue Testing with Thin-Walled Tubular Specimens

2.2 ISO Standards³

- ISO 1099 Fatigue Testing – Axial Force-Controlled Method
- ISO 12106 Fatigue Testing – Axial Strain-Controlled Method
- ISO/TR 12112 - Principles and Designs for Multiaxial Fatigue Testing
- ISO 16842 - Sheet and Strip - Biaxial Tensile Testing Method using a Cruciform Test Piece

3. Terminology

3.1 Definitions and symbols used in this guide are in accordance with Terminologies E6 and E1823.

3.2 *Definitions*—The following symbols and terms are defined specifically in this guide.

3.3 *Symbols:*

- 3.3.1 σ_x —Normal stress in the X-direction
- 3.3.2 σ_y —Normal stress in the Y-direction
- 3.3.3 ϵ_x —Normal strain in the X-direction

³ Available from International Organization for Standardization (ISO), ISO Central Secretariat, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, <https://www.iso.org>.

3.3.4 ε_y —Normal strain in the Y -direction

3.3.5 *Biaxial stress ratio*— $\lambda(\sigma)=\sigma_x/\sigma_y$

3.3.6 *Biaxial strain ratio*— $\lambda(\varepsilon)=\varepsilon_x/\varepsilon_y$

3.3.7 Biaxial phase angle, ϕ is the phase angle between the two loading parameters (normal stresses: σ_x and σ_y or normal strains: ε_x and ε_y)

3.3.8 Equivalent plastic strain (von Mises strain) for yield surface determination, ε_{pl}

4. Summary of Guide

4.1 This standard provides guidance to characterize biaxial deformation, fatigue, and crack growth behaviors of metallic materials subjected to in-plane mechanical forces. Specimens fabricated from plates or sheets of materials in cruciform shapes with four loading arms are used typically in biaxial in-plane testing.

5. Significance and Use

5.1 Deformation and damage under biaxial loading conditions can be significantly different from that typically observed under uniaxial loading conditions. In particular, cyclic hardening in fatigue tests depends upon biaxial loading ratio ($\lambda(\sigma)$ or $\lambda(\varepsilon)$) and biaxial phase angle (ϕ). As a result, fatigue, crack growth, and fracture data generated under uniaxial conditions may not be appropriate for predicting material behavior under biaxial loading conditions. Biaxial deformation and fatigue behaviors of metallic materials are typically investigated with either tubular or planar cruciform-type specimens. ISO technical report (ISO TR/12112) contains a summary of principles and designs of different types of specimens and test equipment used in multiaxial fatigue testing. Practice E2207 provides details for performing strain-controlled axial-torsional fatigue testing with thin-walled tubular specimens. It is not possible to achieve all combinations of biaxial load or strain ratios under combined axial-torsional loading only without using internal and/or external pressurization of the tubular specimens. Moreover, material form available (bars or rods versus plates or sheets) and specific structural applications require evaluation of the material behavior under biaxial loading conditions with planar specimens. In particular, this guide provides relevant details on the following for testing planar cruciform-type specimens:

5.2 Evaluation of material's deformation, fatigue and crack growth behavior under various biaxial loading conditions.

5.3 Generation of biaxial test data at ambient and elevated temperatures, which can be useful for designing engineering components subjected to similar loading conditions and for estimating fatigue crack initiation or crack growth lives of such components.

6. Testing Equipment, Test Specimens, and Testing Programs

6.1 Cruciform specimens typically contain four thick arms for applying biaxial forces and a relatively thin uniform test section (rectangular or circular) in the middle of the specimen. These types of test sections are employed for (a) yield surface

determination (ISO 16842 and Refs. 1-2⁴), (b) strength testing (for example, Ref. 3), (c) fatigue crack initiation, (for example, Refs. 4-6), and (d) fatigue crack growth testing under biaxial loading conditions (Refs. 7, 8, 9, 10). Another type of test section can involve a two-dimensional hourglass shape or continuously reducing thickness in the middle of the test specimen. Such a specimen design might be preferable for conducting crack growth tests under biaxial loading. Schematic of an in-plane biaxial cruciform specimen suggested by Wilson and White is shown in Fig. 1 (Ref. 11). In this figure, T and t denote thicknesses of loading arms and test section, respectively. The test section is circular with a diameter, d and r is the radius of curvature between the test section and the loading arms. Typical test section thickness is 2.5 mm and d/t ratios can vary from 0 to 12.

6.2 Cruciform specimen geometry requires optimization to minimize stress concentrations in the gage section (circular or nearly square-type reduced section) and around the four loading arms of the test specimen. Finite element analyses (elastic or elasto-plastic based on the testing program's requirements) are extensively used to achieve the objective of acceptable stress or strain variations within the test section of cruciform specimen (Refs. 5, 12-14). If needed, tensile and compressive properties of the test specimen's material can be determined with Test Methods E8/E8M, E9, and E209. In addition to reducing stress or strain concentrations in the test section of the specimen, slotted loading arms can reduce stresses in transition regions between loading arms and the test section (Refs. 2, 6, 7, and 12). Examples of two cruciform specimens with slotted loading arms utilized by test laboratories are shown in Fig. 2 and Fig. 3. Trautman, Doker, and Nowack described four cruciform specimens for in-plane biaxial testing in Ref. (6): (1) Specimen for monotonic loading up to extremely high deformation, (2) Specimen for fatigue crack initiation, (3) Specimen for fatigue crack growth measurements, and (4) Specimen for determining crack resistance curves. One more example of cruciform specimen utilized for biaxial fatigue without slotted loading arms is shown in Fig. 4. A balance between the stability of the specimen (to avoid out-of-plane deformation or buckling) particularly under biaxial compressive loading and uniformity of the stress field through the thickness of the specimen is essential. To avoid any anisotropic stress and deformation responses in the test section, a minimum of 10-20 grains through the thickness of the test specimen are recommended (E3, E112, and E2207).

6.3 Biaxial test systems typically contain four actuators and exist in both horizontal and vertical layout of the test configurations. An example of in-plane biaxial test system in the vertical configuration is available in Ref. 2. Test system requires unique design features for multiaxial fatigue testing at high strains, which occur during low-cycle fatigue testing (Ref. 15). For testing under fully-reversed loading conditions involving tension and compression, anti-buckling guides may be

⁴ The boldface numbers in parentheses refer to a list of references at the end of this standard.

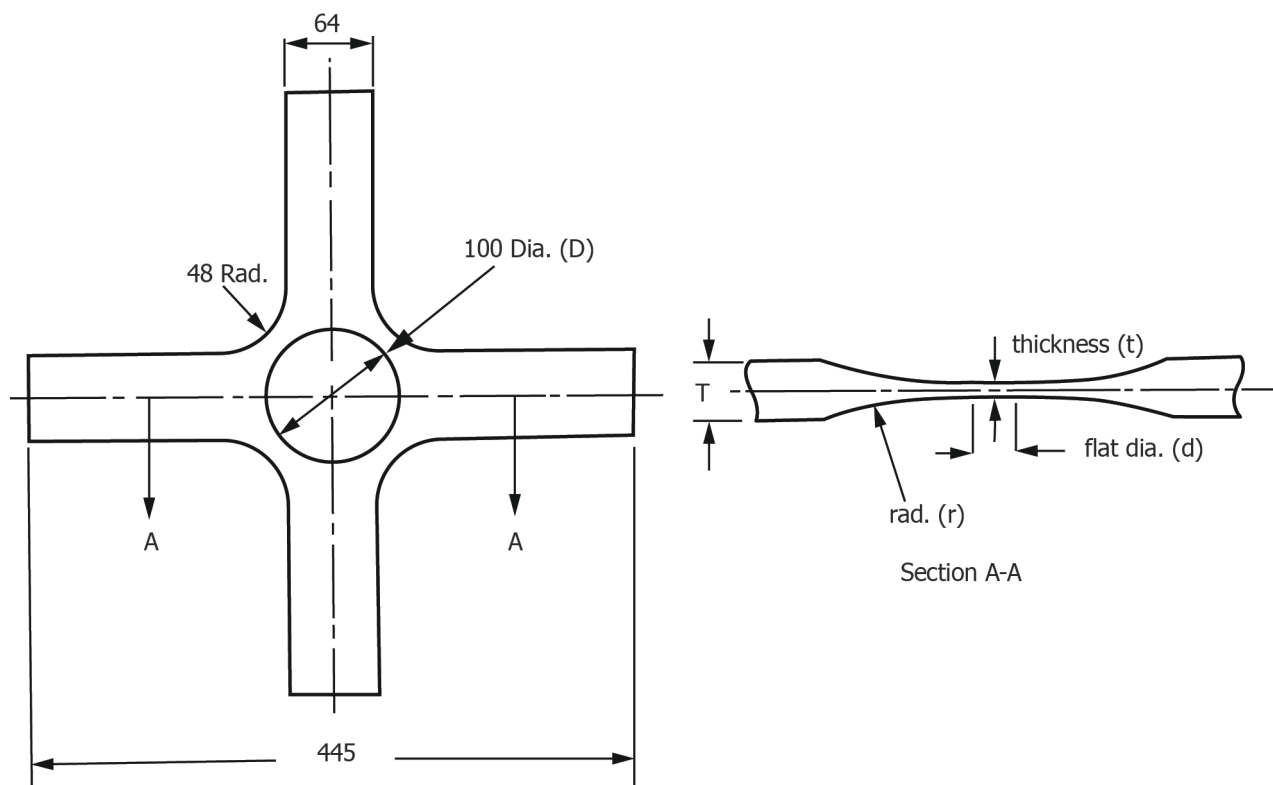


FIG. 1 Schematic of biaxial cruciform test specimen; All dimensions are in mm; t = test section thickness; d = diameter of flat test section; r = radius of curvature between flat test section and the loading arms; D = Diameter of the reduced section; and T = thickness of the loading arms (adapted with SI units from Ref. 11: Wilson, I. H. and White, D. J., "Cruciform Specimens for Biaxial Fatigue Tests: An Investigation Using Finite-Element Analysis and Photoelastic-Coating Techniques, The Journal of Strain Analysis for Engineering Design, Volume 6, Issue 1, 1971, <https://doi.org/10.1243/03093247V06I027>)

necessary depending on the geometry of the cruciform specimen (Ref. 5). Axial forces shall be measured with separate transducers for each axis. The transducer(s) shall be placed in series with the force trains and shall comply with the specifications in Practices E4 and E467.

6.4 Test system can be controlled using forces or displacements, with either independent control of all four axes or centroid control. The latter mode of control is preferred for tracking any damage or crack growth using either an optical microscope or digital image correlation (DIC). Centroid control allows tracking of the optical field of view for a longer duration, as the loading on the specimen is increased. If DIC is used, centroid control will also avoid any decorrelation issues related to the optical pixels moving outside the cameras' field of view. A control method for limiting offsets of the center of a cruciform specimen in a biaxial test is described by Albright and Johnson (Ref. 16).

6.5 Alignment of biaxial test systems involves a strain-gaged, cruciform test specimen with strain-gages mounted to verify alignment in two perpendicular directions. This is an alignment requirement in two dimensions, which is an extension of alignment requirement specified in E1012 for uniaxial flat, rectangular cross-section specimens. Instead of using a

strain-gaged, cruciform specimen for aligning the test system, DIC technique is another option to verify alignment of the test system in two perpendicular directions.

6.6 Biaxial extensometers (verified and classified according to Practice E83), clip gages, and DIC can be used for displacement measurements during in-plane biaxial testing on cruciform specimens in two perpendicular directions. An example of in-plane, contact-type biaxial extensometer is available in (Ref. 17). Contact forces for probes of the extensometer should be optimal to achieve a balance between slippage, which is possible due to low contact forces, and large local stresses due to high contact forces, which can lead to crack initiation during biaxial fatigue testing. For notch-sensitive materials, non-contact, full-field, strain measurement systems such as DIC, are preferable to contact extensometers. For monitoring crack tip opening displacements in biaxial crack growth tests clip gages are often used.

6.7 For high temperature in-plane biaxial testing, test specimens are typically heated to the required temperature by resistance devices (Ref. 9) with electrical current or radiant quartz lamp furnaces (Ref. 2). Other potential options for heating cruciform specimens to test temperatures are induction and susceptor-based heating systems.

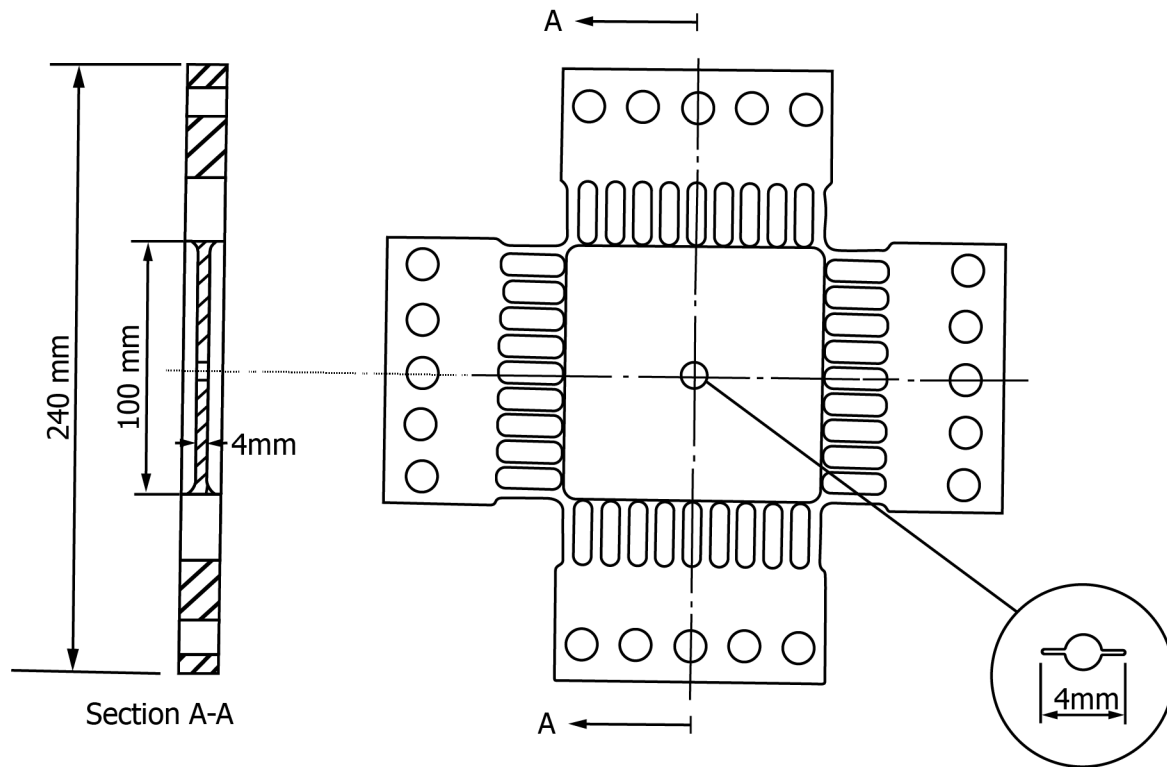


FIG. 2 Cruciform Specimen Geometry for Crack Growth under Biaxial Loading (All Dimensions in mm) [adapted from Ref. 7: Brown, M. W. and Miller, K. J., Mode I Fatigue Crack Growth under Biaxial Stress at Room and Elevated Temperature, Multiaxial Fatigue, ASTM STP 853, K. J. Miller and M. W. Brown, Eds., American Society for Testing and Materials, Philadelphia, 1985, pp. 135-152]

6.8 Computer-based digital data acquisition systems are preferred to acquire force, displacement, and temperature data during biaxial deformation, fatigue crack initiation, and fatigue crack growth testing.

7. Types of In-Plane Biaxial Tests

7.1 This standard guide addresses three types of in-plane biaxial tests on cruciform specimens: (a) deformation and fracture, (b) fatigue crack initiation, and (c) fatigue crack propagation.

7.1.1 *In-Plane Biaxial Deformation and Fracture*—Testing programs in this category explore yield surfaces and biaxial strength of metallic materials subjected to loading along two perpendicular directions. Yield surface in the biaxial stress space is determined by force excursions along different biaxial ratios and monitoring the resulting equivalent plastic strain (von Mises strain) $\Delta\epsilon_{pl}$ for yield surface determination (ISO 16842). Often finite element analysis is used in conjunction with the experimental data to determine biaxial yield surface for a material (Ref. 18). An example of yield curves generated with cruciform specimens under biaxial loading conditions is shown in Fig. 5 (Ref. 1). For in-plane biaxial fracture tests, thin test sections are required for cruciform specimens to ensure biaxial state of stress until failure in the test specimens (Ref. 3).

7.1.2 *Biaxial Fatigue Crack Initiation*—Fatigue tests under biaxial cyclic loading tests can be conducted under various biaxial loading conditions to study the influence of biaxial stresses on the fatigue durability of materials and how this

behavior deviates from fatigue durability under uniaxial loading conditions. Thermoelastic stress analyses are useful for measuring strain fields, detecting cracks, and measuring crack lengths under biaxial loading conditions (Ref. 14). Examples of biaxial, strain-controlled fatigue data generated with cruciform specimens and influence of principal strain ratio, $\lambda(\epsilon)$ on biaxial fatigue life are shown in Fig. 6 and Fig. 7, respectively (Ref. 4). General procedures for conducting force-controlled fatigue tests are available in E466 and ISO 1099. Methodologies for performing strain-controlled fatigue tests are specified in E606/E606M and ISO 12106.

7.1.3 *Biaxial Fatigue Crack Growth and Propagation*—Cruciform test specimens for biaxial fatigue crack growth and propagation under biaxial loading conditions, usually contain a hole, a machined notch, or some other type of feature to generate a sharp crack (Fig. 2). Orientation of this feature and/or biaxial loading ratio are used generate either Mode I, Mode II, or different combinations of Mode I and Mode II types of loading for the crack to propagate under cyclic biaxial loading. Crack resistance curves can be generated under biaxial loading conditions with cruciform specimens. Influence of biaxial loading conditions on crack resistance curves is schematically shown in Fig. 8. Experimental data and crack resistance curves generated with cruciform specimens fabricated from Al 7475-T761 alloy under different biaxial loading ratios were reported by Trautman et al. (Ref. 6). Crack Resistance Curves under Biaxial Loading Conditions are shown schematically in Fig. 8. Rudimentary stress ratio