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Standard Test Method for
Ductility Testing of Metallic Foil[1]

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1. Scope

1.1 This test method covers the determination of ductility, that is, the ability to undergo plastic deformation in tension or bending before fracturing, of metallic foil in thicknesses up through 0.150 mm (0.0059 in.).

1.2 Values stated in SI units are to be regarded as the standard. Inch-pound units are provided for information only.

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 and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 3 Methods of Preparation of Metallographic Specimens[2]
E 6 Terminology Relating to Methods of Mechanical Testing[2]
E 8 Test Methods for Tension Testing of Metallic Materials[2]
E 111 Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus[2]
E 345 Test Methods of Tension Testing of Metallic Foil[2]
E 513 Definitions of Terms Relating to Constant-Amplitude Low-Cycle Fatigue Testing[3]
E 606 Practice for Strain Controlled Fatigue Testing[2]
E 1150 Definitions of Terms Relating to Fatigue[2]

3. Terminology

3.1 *Definitions:*

3.1.1 The definitions of terms appearing in Definitions E 6, E 1150, E 513, and Practice E 606, shall be considered as applying to the terms used in this test method.

3.1.2 *fatigue ductility, D_f* —the ability of a material to deform plastically before fracturing, determined from a constant-strain amplitude, low-cycle fatigue test.

NOTE 1—Fatigue ductility is usually expressed in percent in direct analogy with elongation and reduction of area ductility measures.

NOTE 2—The fatigue ductility corresponds to the fracture ductility, the true tensile strain at fracture. Elongation and reduction of area represent the engineering tensile strain after fracture.

NOTE 3—For the purpose of this definition the fatigue ductility exponent, c, is defined as $c = -0.60$ (see equation in 9.1).[4]

4. Summary of Test Method

4.1 The specimen is subjected to a fatigue test which employs precisely controlled, symmetric, cyclic, constant-amplitude, flexural strains of a magnitude that will cause fracture in the low-cycle fatigue regime.[4]

4.2 The fatigue ductility is determined from an equation derived from universal, empirical, relationships between tensile properties and fatigue behavior which utilizes the strain range employed and the fatigue life obtained in the fatigue test, as well as the modulus of elasticity, the tensile strength and the fracture strength determined in accordance with Test Method E 111 and Test Methods E 8, with the provisions in Test Methods E 345 and in this standard.

5. Significance and Use

5.1 For bulk specimens, tension tests provide an adequate means to determine the ductility of materials either through the measurement of elongation or reduction of area. For foil specimens, however, tension tests are not very useful for the determination of ductility. This test method, employing low-cycle fatigue, circumvents the difficulties arising from the continuous application of strain until fracture and determines the ductility indirectly from empirical low-cycle fatigue relationships for metals.

5.2 The results of ductility tests from selected portions of a metallic foil may not totally represent the ductility of the entire foil or its in-service behavior in different environments.

5.3 This test method is considered satisfactory for acceptance testing of commercial shipments, design purposes, service evaluation, manufacturing control, and research and development.

6. Apparatus

6.1 *Fatigue Ductility Flex Tester* as schematically shown in Fig. 1. A photograph of the tester is shown in Fig. 2.[5] The tester consists of a juxtaposed pair of precision test mandrels moving

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[1] This test method is under the jurisdiction of ASTM Committee E-28 on Mechanical Testing and is the direct responsibility of Subcommittee E28.02 on Ductility and Flexure Testing.

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

[3] Discontinued—See *1986 Annual Book of ASTM Standards*, Vol 03.01.

[4] Engelmaier, W., "A Method for the Determination of Ductility for Thin Metallic Materials," *Formability 2000 A.D., ASTM STP 753*, ASTM, 1981, in press.

[5] Model 2 FDF Flex Ductility Tester, manufactured in accordance with the original Bell Laboratories design, available from Universal Tool and Machine, Inc., 171 Coit St., Irvington, NJ 07111, has been found satisfactory.

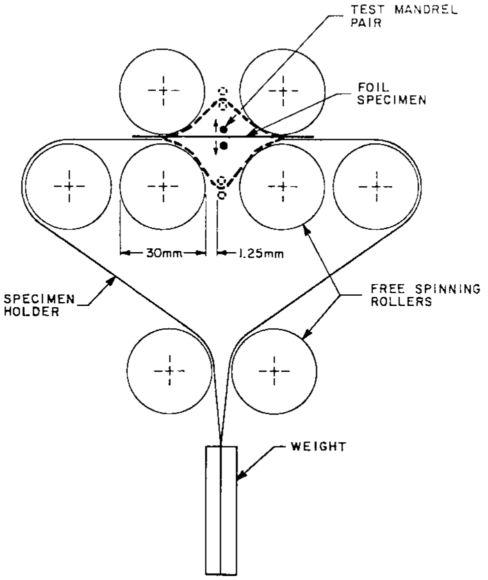

FIG. 1 Schematic of Fatigue Ductility Flex Tester Showing Principle of Operation

FIG. 2 Fatigue Ductility Flex Tester, Model 2 FDF

vertically a total of 38 ± 3 mm (1½ ± ⅛ in.) at 50 cycles/min. The specimen, held in a horizontal position by six rollers and positioned between the two test mandrels, is subjected to cyclic flexural strains by being bent alternately around the two test mandrels. The precision test mandrels shall have uniform roundness, a maximum surface roughness height of 0.25 µm (10 µin.), and a minimum surface hardness of 60 HRC. The diameter of the test mandrels used shall be measured within 1 %. The specimen is held in an invariant position relative to the test mandrels by a tension weight. The tension weight, together with the specimen-holder loop (see Fig. 1), provides for precisely repeated contact between the specimen and the test mandrels. The weight tension also serves to assure conformance of the specimen to the test mandrel curvature. The tensile stress due to the tension weight shall not exceed 10 % of the yield strength (0.2 % offset, determined in accordance with Test Methods E 8 with the provisions in Test Methods E 345) of the material. A 100-g (3-oz) tension weight is suitable for most specimens; however, for very thin foil specimens it might be necessary to use a lighter tension weight.

6.2 *Double-Bladed Specimen Cutter,*[6] as required in Test Methods E 345, but capable of cutting specimens to the width required herein (Section 7).

7. Test Specimens

7.1 *Specimen Preparation*—Test specimens shall be prepared in accordance with Test Methods E 345, Type B specimens, with the dimensions as specified herein. The specimens may be prepared individually by use of a double-bladed cutter. The cutting edges of the blades should be lubricated with a material such as stearic acid in alcohol or other suitable material. The finished specimens shall be examined under about 20 × magnification to ascertain that the edges are smooth and that there are no surface scratches or creases. Specimens showing discernible surface scratches, creases, or edge discontinuities shall be rejected.

7.2 *Specimen Thickness*—Specimen thickness shall be determined in accordance with Test Methods E 345. The thickness of each specimen may be determined by any suitable means, provided that the thickness of each specimen is measured to an accuracy of 2 %.

NOTE 4—For specimens for which the density is not known, for example, plated foil, the thickness of the specimens will have to be measured directly even for soft materials or materials thinner than 0.025 mm (0.001 in.).

NOTE 5—For specimens with rough surfaces, it is necessary to determine the minimum core thickness, that is, the specimen thickness without the rough surface features, from a metallographic cross section, prepared in accordance with Methods E 3.

7.3 *Specimen Dimensions*—The test specimens shall have the following dimensions:

7.3.1 *Width*—2.5 to 7.5 mm (0.1 to 0.3 in.) with 3.2 mm (0.125 in.) the preferred width.

7.3.2 *Length*—30 mm (1.2 in.) minimum.

7.4 *Number of Specimens*—It is recommended that at least three specimens in both the main orientation direction (direction of rolling for wrought foil, direction of plating solution agitation for plated foil) and the orthogonal direction be tested.

7.5 *Mechanical Properties*—For purposes of performing the test and calculating the fatigue ductility, it is desirable to have available in both the main orientation direction and the orthogonal direction the following mechanical properties, obtained in accordance with the applicable standards such as Test Methods E 8, Test Method E 111, and Methods E 345: tensile yield strength, tensile strength, tensile fracture strength, and modulus of elasticity.

NOTE 6—It is only necessary to determine these mechanical properties on a representative basis for the metallic foil to be tested, since these properties have only a secondary effect on the calculation of the fatigue

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[6] The Model JDC-125 Precision Sample Cutter, available from Thwing-Albert Instrument Co., 10960 Dutton Road, Philadelphia, PA 19154, has been found satisfactory.

ductility. The variation in D_f with variations in the mechanical properties is shown in Appendix X1.

NOTE 7—For many foils, in particular plated foils, the fracture strength is identical to the tensile strength.

8. Procedure

8.1 In general, the test is carried out at ambient temperature within the limits of 10 to 35°C (50 to 95°F). Tests carried out under controlled conditions shall be made at a temperature of 23 ± 5°C (73 ± 9°F).

8.2 Attach the specimen to flexible specimen holders with adhesive tape and clamp tension weight to specimen holders to form loop as shown in Fig. 1.

NOTE 8—The purpose of the specimen holders is the formation of the specimen-holder loop shown in Fig. 1. Thus, the sample holders can be any material, for example, paper, epoxy-impregnated glass cloth, etc., that can support the tension weight and is flexible enough to be easily wrapped around the rollers. The recommended specimen holder width is 12.5 mm (0.5 in.) and the total specimen-holder assembly length shall be 480 ± 40 mm (19 ± 1.5 in.).

8.3 Select a test mandrel diameter that will result in a specimen fatigue life between 30 and 500 cycles to failure and mount test mandrel pair on fatigue ductility flex tester.

NOTE 9—The choice of test mandrel diameter has no effect on the fatigue ductility value, provided the obtained fatigue life falls within $30 \leq N_f \leq 500$ cycles. Fatigue life results outside this range give fatigue ductilities which can increasingly deviate from the properly obtained values.[4,7]

NOTE 10—For most metallic foils, a set of test mandrels with 1-mm (0.039-in.); 2-mm (0.079-in.), and 5-mm (0.197-in.) diameters will provide fatigue lives in the 30 to 500-cycle range for samples ranging from thin, ductile to thick, brittle foils.

8.4 Adjust the horizontal roller position to a spacing of 1.25 mm (0.05 in.) between the test mandrels and the rollers.

8.5 Place specimen-holder loop between test mandrels and rollers as shown in Fig. 1 and Fig. 2.

8.6 Fatigue test specimen to failure by separation of the specimen and record the fatigue life.

9. Calculations

9.1 Calculate the fatigue ductility for each specimen by iteratively solving the empirical formula:[4]

$$N_f^{-0.6} D_f^{0.75} + 0.9(S_u/E) \cdot [(S_f/S_u)(\exp(D_f)/0.36)]^{0.1785\log(10^5/Nf)} - (2t_M/2_\rho + t) = 0$$

where:

N_f = fatigue life, number of cycles to failure,
D_f = fatigue ductility (× 100, %),
S_u = tensile strength of specimen material, MPa (or psi),
E = modulus of elasticity of specimen material, MPa (or psi),
S_f = fracture strength of specimen material, MPa (or psi),
t_M = minimum core thickness of specimen, (t less thickness of surface roughness/adhesion treatment, for specimens with smooth surfaces $t_M = t$), mm (or in.),
2ρ = test mandrel diameter, mm (or in.), and
t = thickness of specimen, mm (or in.).

NOTE 11—Footnote 8 gives a program for programmable calculators to evaluate the fatigue ductility formula.[8]

NOTE 12—The terms in the fatigue ductility formula are in order: the Manson-Coffin plastic strain-fatigue life relationship, the elastic strain-fatigue life relationship, and the cyclicly applied strain range.[5]

9.2 Calculate the average fatigue ductility and the sample standard deviation in accordance with Definitions E 1150 for the number of specimens tested in each orientation direction.

10. Report

10.1 The report shall include the following:

10.1.1 Description of material, including name of manufacturer, method of manufacture, chemical composition, thermal and mechanical history,

10.1.2 Separately for each material orientation tested:

10.1.2.1 Specimen dimensions,

10.1.2.2 Test mandrel diameter used,

10.1.2.3 Range of fatigue lives obtained,

10.1.2.4 Tensile properties used in calculation of fatigue ductility, and

10.1.2.5 Fatigue ductility, including orientation of length of specimens, number of specimens, and sample standard deviation.

11. Precision and Bias

11.1 The precision of this test method is controlled by the tolerance allowed in the measurement of the test specimen thickness. The thickness tolerance of ±2 % can result in variations in ductility of about ±3 %. The natural distributional variation of material properties also has an impact on the obtainable precision of the results. A round-robin study on copper foil[8] involving seven test laboratories has shown that the precision of this test method produced standard deviations in the laboratory-to-laboratory results which typically are 10 to 15 % of the mean ductility value.

11.2 There is no known bias inherent in this test method. In the absence of an absolute standard it is not possible to determine if a bias exists.

11.3 The accuracy of this test method is controlled primarily by the accuracy of the test specimen thickness and test mandrel diameter, and secondarily by the accuracy of the mechanical properties used in the fatigue ductility formula. The variation in D_f with variation in these parameters is shown in Appendix X1.

12. Keywords

12.1 ductility; foil; fatigue ductility

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[7] Supporting data is available from ASTM Headquarters. Request RR: E28-1007.

[8] Engelmaier, W., "Fatigue Ductility for Foils and Flexible Printed Wiring," *Program No. 01883D*, HP-67/97 User's Library, Hewlett Packard Co., Corvallis, OR, 1978.

APPENDIX

(Nonmandatory Information)

X1. EXAMPLE AND PARAMETER VARIATION EFFECTS

X1.1 The test specimen consists of electroplated, smooth copper foil for which the following mechanical properties in the sparging direction are known:

$$S_u = 266 \text{ MPa } (38\,500 \text{ psi})$$

$$E = 82\,800 \text{ MPa } (12.0 \times 10^6 \ psi)$$

$$S_f = S_u$$

With a vernier micrometer the diameter of the precision test mandrels has been measured to be $2\rho = 1.99$ mm (0.0783 in.) and the thicknesses of three specimens with their long dimension coinciding with the sparging direction have been determined as: $t_1 = 0.0381$ mm (0.00150 in.), $t_2 = 0.0343$ mm (0.00135 in.), and $t_3 = 0.0343$ mm (0.00135 in.). The fatigue lives obtained for these three specimens are: $N_{f,1} = 100$, $N_{f,2} = 100$, $N_{f,3} = 110$ cycles-to-failure. Solving the fatigue ductility formula for the three specimens gives: $D_{f,1} = 39.4$ %, $D_{f,2} = 33.7$ %, and $D_{f,3} = 36.4$ %. Thus, the average fatigue ductility for this foil sample is $\bar{D}_f = 36.5$ % with a standard deviation $s = 2.85$.

X1.2 To investigate the variation in D_f caused by errors in the mechanical properties, $D_{f,1}$ recalculates to $D'_{f,1} = 38.5$ % for a value of $S'_u = 1.1\, S_u$ and to $D''_{f,1} = 40.0$ % for a value of $S''_f = 0.9\, S_u$.

X1.3 From the results in X1.1 and X1.2, variations of 10 % in the parameters in the fatigue ductility formula produce the following variations in the fatigue ductility:

Parameter variation	0.90 t	1.10 N_f	1.10 2ρ	1.10 S_u	0.90 S_f
Ductility variation	0.86	1.08	0.87	0.98	1.02