Designation: F1160 – 14

Standard Test Method for Shear and Bending Fatigue Testing of Calcium Phosphate and Metallic Medical and Composite Calcium Phosphate/Metallic Coatings[1]

This standard is issued under the fixed designation F1160; 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 test method covers the procedure for determining the shear and bending fatigue performance of calcium phosphate coatings and of porous and nonporous metallic coatings and for determining the bending fatigue performance of metallic coatings over sprayed with calcium phosphate. This test method has been established based on plasma-sprayed titanium and plasma-sprayed hydroxylapatite coatings. The efficacy of this test method for other coatings has not been established. In the shear fatigue mode, this test method evaluates the adhesive and cohesive properties of the coating on a metallic substrate. In the bending fatigue mode, this test method evaluates both the adhesion of the coating as well as the effects that the coating may have on the substrate material. These methods are limited to testing in air at ambient temperature. These test methods are not intended for application in fatigue tests of components or devices; however, the test method which most closely replicates the actual loading configuration is preferred.

1.2 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the 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 and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E6 Terminology Relating to Methods of Mechanical Testing
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
E468 Practice for Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials
E1012 Practice for Verification of Testing Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application
E1832 Practice for Describing and Specifying a Direct Current Plasma Atomic Emission Spectrometer

3. Terminology

3.1 The definitions of terms relating to shear and fatigue testing appearing in Terminology E6 shall be considered as applying to the terms used in this test method.

3.2 *loading points, n*—objects in contact with the test beam or bar used to apply force to the beam or bar, usually radiused to con concentrate the force to a point or a line.

4. Summary of Test Method

4.1 *Shear Fatigue Testing:*

4.1.1 The intent of the shear fatigue test is to determine the adhesive or cohesive strength, or both, of the coating.

4.1.2 This test method is designed to allow the coating to fail at either the coating/substrate interface, within the coating, or at the interface between the coating and the adhesive bonding agent used to transmit the force to the coating.

4.2 *Bending Fatigue Testing:*

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[1] This test method is under the jurisdiction of ASTM Committee F04 on Medical and Surgical Materials and Devices and is the direct responsibility of Subcommittee F04.15 on Material Test Methods.

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[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.

4.2.1 The primary intent of the bending fatigue test is to quantify the effect that the coating has on the substrate it is applied to. Secondarily, it may be used to provide a subjective evaluation of coating adhesion, (that is, spalling resistance, cracking resistance, and so forth).

4.2.2 This test method is designed to first provide a substrate fatigue strength to serve as a baseline to assess the effects of the coating on the resulting fatigue strength of the system.

5. Significance and Use

5.1 The shear and bending fatigue tests are used to determine the effect of variations in material, geometry, surface condition, stress, and so forth, on the fatigue resistance of coated metallic materials subjected to direct stress for up to 10^7 cycles. These tests may be used as a relative guide to the selection of coated materials for service under condition of repeated stress.

5.2 In order that such basic fatigue data be comparable, reproducible, and can be correlated among laboratories, it is essential that uniform fatigue practices be established.

5.3 The results of the fatigue test may be used for basic material property design. Actual components should not be tested using these test methods.

6. Equipment Characteristics

6.1 Equipment characteristics shall be in accordance with Practice E466, Section 7. See also Practices E467 and E1012 and Terminology E1832.

6.2 *Shear Fatigue Test Grips:*

6.2.1 *General*—Various types of grips may be used to transmit the load to the specimens by the testing machine. To ensure axial shear stress, it is important that the specimen axis coincide with the centerline of the heads of the testing machine and that the coating test plane be parallel to the axial force. Any departure from this requirement (that is, any eccentric loading) will introduce bending stresses that are not included in the usual stress calculation (force/cross-sectional area).

6.2.2 A drawing of a typical gripping device for the test assembly is shown in Fig. 1.

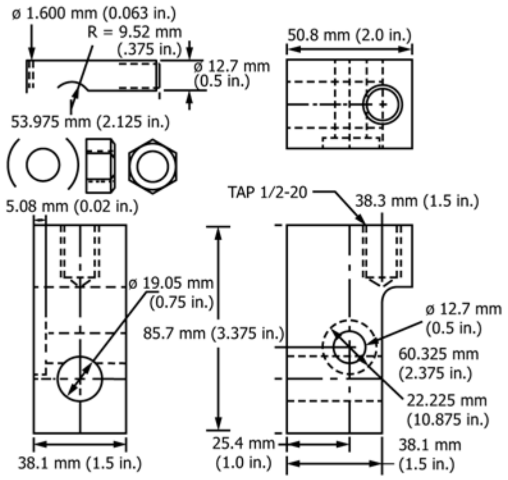


FIG. 1 Gripping Device for Shear Testing

6.2.3 Fig. 2 shows a drawing of the adaptor to mate the shear fixture to the tensile machine

6.2.4 Figs. 3 and 4 show schematics of the test setup.

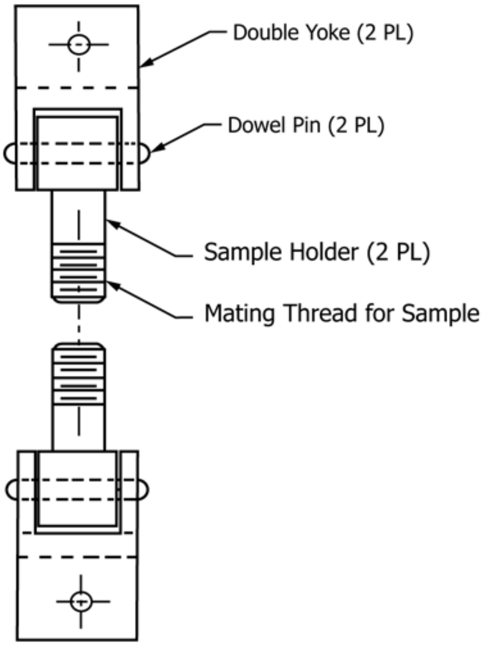
6.3 *Bending Fatigue Test Grips*—There are a variety of testing machines that may be employed for this test (that is, rotating beam fatigue machines and axial fatigue machines). The gripping method for each type of equipment shall be determined by either the manufacturer of that equipment or the user.

7. Adhesive Bonding Materials

7.1 *Adhesive Bonding Agent*—A polymeric adhesive bonding agent in film form, or viscous adhesive cement, shall be identified and shall meet the following requirements.

7.1.1 The bonding agent shall be capable of bonding the coating on the test specimen components with an adhesive shear strength that is at least 34.5 MPa [5000 psi] or as great as the minimum required adhesion or cohesion strength of the coating, whichever is greater. The 34.5 MPa bonding strength is the static strength of the adhesive. The fatigue strength of the adhesive is usually less than that value. In fatigue the coating under test is often stronger than the adhesive causing the fracture to occur at the adhesive interface. If it is desirable to continue a fatigue test after fracture through the adhesive, the test sample may be rebonded and testing.

7.1.2 In instances where coating porosity extends to the coating/substrate interface, the bonding agent shall be sufficiently viscous and application to the coating sufficiently detailed, to ensure that it will not penetrate through the coating



NOTE 1—(2 PL) indicates the top and bottom adapters are identical.

FIG. 2 Adaptor to Mate the Gripping Device to the Tensile Machine

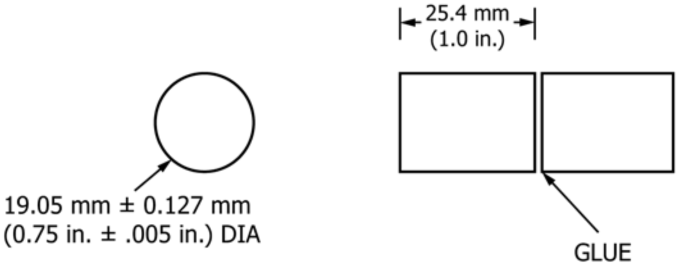


FIG. 3 Schematic of the Shear Test Setup

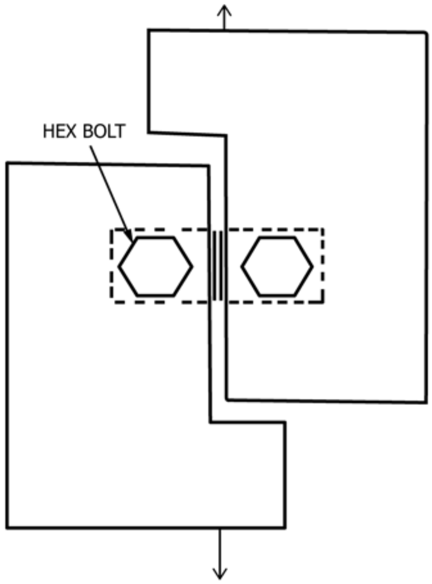


FIG. 4 Drawing of the Recommended Shear Test Specimen Assembly

to the substrate. The FM 1000 Adhesive Film[3] with a thickness of 0.25 mm [0.01 in.] has proven satisfactory for this test method.

7.1.3 If a material other than FM 1000 is used, or the condition of the FM 1000 is unknown, it must be tested to establish its equivalence to fresh FM 1000. Testing should be performed without the presence of the coating to establish the performance of the adhesive. Two alternative adhesives that have been used successfully are HYSOL 9514 and 3M 2214 non-metallic filled. Validation data on Hysol 9514 from Indolab GmbH is presented in Appendix X1. These adhesives may not be suitable for HA coatings because they could penetrate the HA.

8. Test Specimen

8.1 *Shear Fatigue Specimen for Calcium Phosphate and Metallic Coatings Only:*

8.1.1 The recommended shear test specimen and setup is illustrated in Figs. 3 and 4, respectively. A complete assembled test assembly consists of two solid pieces, one with a coated surface and the other with an uncoated surface. The uncoated surface may be roughened to aid in the adhesion of the adhesive bonding agent.

8.1.2 The cross-sectional area of the substrate upon which the coating is applied shall be a nominal 2.85 cm^2 [0.44 $in.^2$]. When specimens of another cross-sectional area are used, the data must be demonstrated to be equivalent to the results produced using the 2.85-cm^2 standard cross-sectional area and the specimen size should be reported.

8.2 *Bending Fatigue Specimen for Calcium Phosphate, Metallic, and Calcium Phosphate-Metallic Composite Coatings:*

8.2.1 The type of specimen used will depend upon the objective of the test program, the type of equipment, the equipment capacity, and the form in which the material is available. The *R* ratio for bending fatigue tests shall be 0.1 or less excluding rotating beam samples. For rotating beam samples the *R* ratio shall be -1.0. However, the design shall meet certain general criteria as follows:

8.2.1.1 The design of the specimen shall be such that if specimen failure should occur, it should occur in the test section (reduced area as shown in Figs. 5-8).

8.2.1.2 Specimens using a flat tapered beam configuration should be designed such that a tapered gauge section with a constant surface stress exists when the specimen is constrained at one end and force applied through loading points perpendicular to and centered on the beam axis at the other end (that is, cantilever loading, usually a tapered cantilever beam as shown in Fig. 10).

8.2.1.3 Four-point bend specimens consisting of straight bars of constant, usually rectangular, cross section loaded in four-point bending also produce a region of constant surface stress in the center span between the two center loading points. The distance between the two external loading points shall always be identical (see Fig. 9).

8.2.1.4 Rotating beam specimens may have unique dimensions, depending upon the type of machine used. Appropriate manufacturers' specifications for these specimens should be used.

8.2.1.5 The tensile surface edges of the flat tapered cantilever beam specimen and the four point bend specimen may be broken to a small non zero radius to avoid stress concentrations at the edge.

8.3 *Specimen Coating Preparation:*

8.3.1 Coatings may be applied by any one of a number of techniques. All test specimens for coating characterization

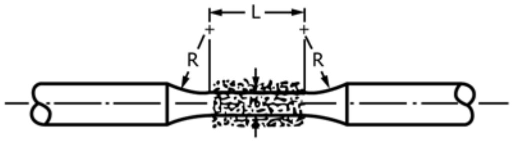


FIG. 5 Bending Fatigue Specimen With Tangentially Blending Fillets Between the Test Section and the Ends for Rotating Beam or Axial Loading

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[3] The sole source of supply of the apparatus known to the committee at this time is Cytec Engineered Materials, Inc., 1300 Revolution St., Havre de Grace, MD 21078. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

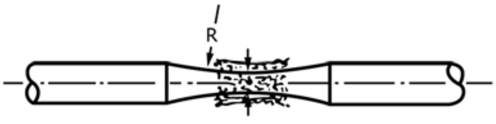

FIG. 6 Specimens With a Continuous Radius Between the Ends for Rotating Beam or Axial loading

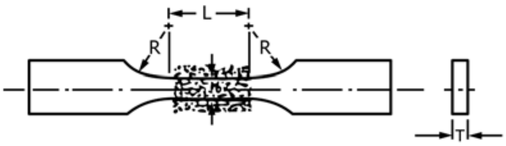

FIG. 7 Specimens With Tangentially Blending Fillets Between the Uniform Test Section and the Ends for Axial Loading

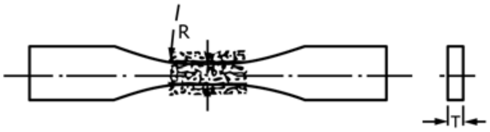

FIG. 8 Specimens With a Continuous Radius Between the Ends for Axial Loading

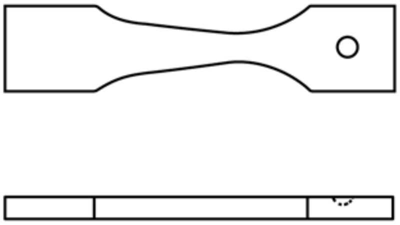

FIG. 10 Tapered Beam Configuration for Bend Testing

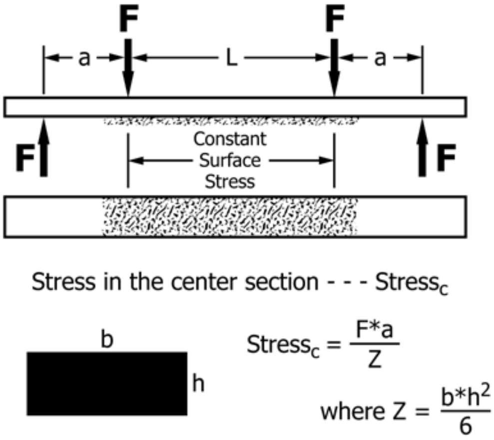

FIG. 9 Four-pointed Bend Test Configuration and Stress Calculation for a Rectangular Cross Section Test Piece

shall be prepared from indicative coating lots, using production feedstock lots and be coated on the same equipment used for actual implants. The coating should consist of a layer which is mechanically or chemically attached and covers the surface.

8.3.2 Coatings should be applied as follows:

8.3.2.1 For the shear fatigue specimens, the coating should be applied to the 19.05-mm [0.75-in.] diameter face only (see Fig. 3).

8.3.2.2 For the rotating beam and axial fatigue test specimens the coating shall be applied all around and extend slightly beyond the reduced sections (see Figs. 5-8). For the tension-tension bending fatigue specimens, the coating shall be applied to the side that will be loaded in tension only. The coating shall extend well beyond the tapered gauge area to keep stress concentrations at the transition from coated surface to uncoated surface out of the high stress regions (Fig. 10) On the four-point bend test sample the coating shall be extended outside of the inner loading points to keep a possible stress concentration at the transition from coated surface to uncoated surface outside the maximum stress center region.).

8.3.3 All thermal treatments normally performed on the devices should be performed on the test specimens.

8.3.4 If used, passivation and sterilization techniques should be consistent with those used for actual devices.

8.3.5 *Inspection*—Before testing, visual inspections should be performed on 100 % of the test specimens. Non-uniform coating density shall be cause for specimen rejection. For the shear fatigue specimen, lack of coating on the coated face shall be cause for specimen rejection. For the bending fatigue specimen, lack of coating in highly stressed regions shall be cause for specimen rejection.

9. Procedure

9.1 The number of specimens required for testing, as well as the test methods in which the fatigue data may be interpreted, can vary. Several test methods are referenced in this test method.[4,5,6]

9.2 The type of specimen used will depend upon the objective of the test program, the type of equipment available, the equipment capacity, and the form in which the material is available. The specimen chosen should come as close to matching the intended application as possible.

9.3 The test frequency used shall not exceed 50 Hz for rotating beam tests and 30 Hz for bending fatigue tests. The test frequencies should be carefully selected to avoid inertial effects from the mass of the test fixtures.

9.4 *Shear Fatigue Specimens:*

9.4.1 *Curing the Adhesive*—The test results achieved are greatly dependent upon the adhesive used and the way in which it is cured. One suggested adhesive is FM 1000 having a thickness of 0.25 mm [0.01 in.]. This material has successfully been cured using the following cycle:

9.4.1.1 Align the adhesive with the surface of the coating, taking precautions to align the adhesive in the center of the coating.

9.4.1.2 Apply a constant force using a calibrated high temperature spring, resulting in a stress of 0.138 to 0.295 MPa [20 to 43 psi] between the coating and the opposing device that will test the coating.

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[4] Collins, J.A., *Failure of Materials in Mechanical Design*, John Wiley & Sons, New York, 1981.

[5] *Handbook of Fatigue Testing, ASTM STP 566*, ASTM, 1974.

[6] Frost, N. C., Marsh, K. J., and Pook, C. P., *Metal Fatigue*, Oxford University Press, London, 1974.

(1) Care shall be taken to maintain alignment of the coating and the matching counterface during the test.

9.4.1.3 Place the assembly in an oven and heat at 176°C for 2–3 h.

(1) The exact amount of time necessary to cure the adhesive shall need to be determined by each user, as oven temperature may vary with load size and oven type. It is suggested that the curing cycle be optimized first without the coating present.

9.4.1.4 Remove the cured assembly from the oven and allow it to cool to room temperature.

9.4.1.5 Remove all excess adhesive which has protruded from the coated surface. Demonstrate that this process does not compromise the integrity of the test result.

9.4.2 Place the specimen assembly in the grips so that the long axis of the specimen is perpendicular to the direction of the applied shear load through the centerline of the grip assembly (see Fig. 3).

9.4.3 Specimens for which the adhesive has penetrated to the substrate shall be discarded and the results not included in the analysis and report.

9.5 *Bending Fatigue Specimens:*

9.5.1 Appropriate testing of the uncoated substrate material, upon which the coating will be applied, should be performed to establish a baseline from which to assess the effect of the coating.

9.5.1.1 The baseline test specimens may or may not be grit-blasted depending upon the objective of the test. In either event, the surface roughness should be reported.

9.5.1.2 For composite calcium phosphate-metallic coatings, additional baseline testing of specimens with only the metallic coating should also be preformed to allow an assessment of the effects of each coating.

9.5.2 When mounting the specimen, alignment is crucial. Factors such as poorly machined specimens and misalignment of machine parts might result in excessive vibration leading to erroneous results.

9.5.3 For the rotating beam test, do not apply the load until the machine is operating at the frequency desired for testing.

9.5.4 For the purpose of calculating the applied loads on the test specimen, to determine the applied stresses, measure the dimensions from which the substrate area is calculated to the nearest 0.03 mm [0.001 in.] for dimensions equal to or greater than 5.08 mm [0.200 in.] and to the nearest 0.013 mm [0.0005 in.] for dimensions less than 5.08 mm [0.002 in.].

9.5.4.1 For the coated specimens, the uncoated substrate dimensions should be used to calculate the applied stress. For some coating processes that apply pressure to the coating, there could be some deformation of the surface of the coated cross section. It may be necessary to modify the stress calculations based on the actual solid cross section.

9.5.5 Any fracture which occurs outside the gauge section shall be rejected.

10. Test Termination

10.1 Continue the testing until the specimen fails or until a predetermined number of cycles has been reached (typically 10^7 cycles). Failure may be defined as: (*1*) complete separation of the coating, (*2*) visible cracking at a specified magnification, (*3*) a crack of certain dimensions, (*4*) or some other criterion.

11. Stress Calculation

11.1 *Shear Fatigue Specimens*—Calculate the substrate area upon which the coating is applied to the nearest 0.06 cm^2 [0.01 in.^2]. Record peak (failure) load and calculate failing stress in megapascals [pound-force per square inch] of adhesive area as follows:

$$S = F/A \tag{1}$$

where:

S = adhesion or cohesion strength,
F = maximum load to failure, and
A = cross-sectional area.

11.2 *Bending Fatigue Specimens*—For the purpose of calculating the applied loads on the test specimen to determine the applied stresses, measure the dimensions from which the substrate adhesive area is calculated to the nearest 0.03 mm [0.001 in.] for dimensions equal to or greater than 5.08 mm [0.200 in.] and to the nearest 0.013 mm [0.0005 in.] for dimensions less than 5.08 mm [0.200 in.].

12. Report

12.1 The test report procedure and results shall be in accordance with Practice E468 and include the following information:

12.1.1 Identification of the materials used in the specimen, including bonding agent used;

12.1.2 Identification of methods used to apply the coating including the coating method, heat treatment, or other data if available including date, cycle number, and the time and temperature of the adhesive cure method;

12.1.3 Dimensional data including the bond cross-sectional area and the thickness of the coating;

12.1.4 Number of specimens tested;

12.1.5 All values for the applied stress and cycles to failure (or run-out);

12.1.6 The mode of failure (for example, cohesive versus adhesive) and location for each test specimen. (This may also be performed at various intervals during the test.);

12.1.7 The criteria selected for failure, including the number of cycles chosen for run-out;

12.1.8 Report the R ratio (minimum stress/maximum stress);

12.1.9 The test frequency;

12.1.10 The specimen size for the shear fatigue test if different than the standard size;

12.1.11 The substrate surface roughness for the baseline bending fatigue test;

12.1.12 Location of the fracture.

13. Precision and Bias

13.1 *Review of the Round Robin*—Six laboratories were involved in round-robin testing. Each laboratory was provided with 12titanium-6aluminum-4vanadium rotating beam specimens coated with plasma-sprayed titanium. Specimens were tested at 90 000 psi.

13.2 Table 1 shows the cycles to failure raw data generated from each laboratory.

13.3 *h Graph:*

13.3.1 The *h* value evaluates the consistency of the test results from laboratory to laboratory.

13.3.2 There are three patterns in these plots. In one pattern, all values are either positive or negative. In the second pattern, there are roughly the same number of laboratories that exhibit positive values as those that exhibit negative values. In the third type, one laboratory exhibits a value that is opposite of the other laboratories. The first two types are considered normal. The third type warrants further evaluation.

13.3.3 Fig. 11 shows the *h* values for each laboratory.

13.4 The *k* value evaluates the consistency of the test results within each laboratory.

13.4.1 *k Graph:*

13.4.1.1 The *k* value evaluates the consistency of the test results within each laboratory.

13.4.1.2 The pattern to look for in the *k* graph is a laboratory having a very large or a very small *k* value. High values indicate imprecision. Very small values indicate a very insensitive measurement scale or other measurement problems. A *k* value greater than 1 indicates greater variability than other laboratories.

13.4.1.3 Fig. 12 shows the *k* values for each laboratory.

13.5 *Precision Statistics*—The precision statistics are shown in Table 2.

14. Keywords

14.1 ceramic coatings; composite coatings; fatigue testing; hydroxylapatite; metallic coatings; plasma-sprayed coatings; porous coatings; tribasic calcium phosphate

TABLE 1 ASTM F1160 Round Robin, Cycles to Failure

Source[A]	1	2	3	4	5	6
	83 300	78 000	run out	64 700	64 200	71 900
	53 500	62 300	26 800	78 800	136 300	51 000
	80 400	92 200	16 900	137 200	57 000	88 100
	67 900	36 300	28 700	175 100	48 700	51 200
	64 900	73 400	17 900	116 400	32 100	58 200
	89 400	98 200	70 700	211 100	61 300	42 400
	51 000	49 100	52 900	183 100	45 100	58 400
	72 500	63 600	22 500	200 500	77 900	84 200
	46 600	118 200	23 300	161 200	40 000	64 600
	54 800	40 700	38 000	111 100	55 400	44 800
	48 100	82 800	36 800	277 500	38 100	73 300
	97 700	72 700	. . .	183 100	56 800	66 400
Average	67 517 ± 17 277	72 292 ± 22 009	33 450 ± 11 622	158 317 ± 60 157	59 408 ± 27 312	62 875 ± 14 653

[A] 1 = Biomet.
2 = Osteonics.
3 = Wright Medical.
4 = EML.
5 = Zimmer.
6 = Howmedica.

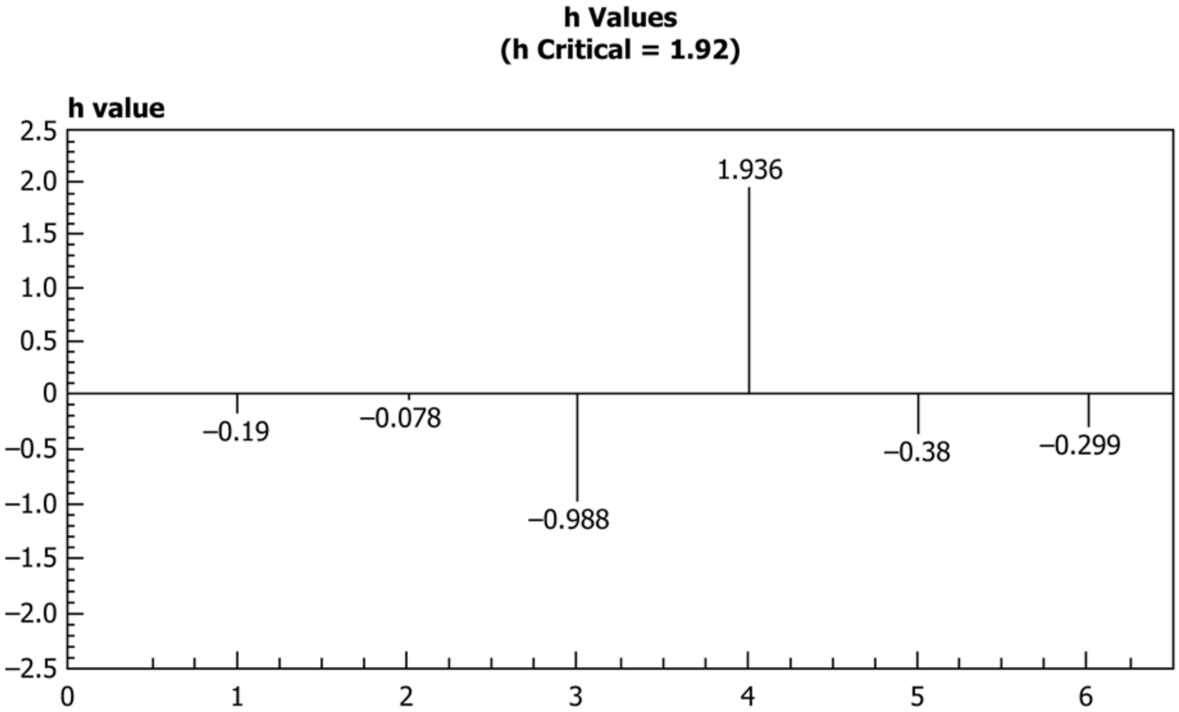

FIG. 11 *h* Values

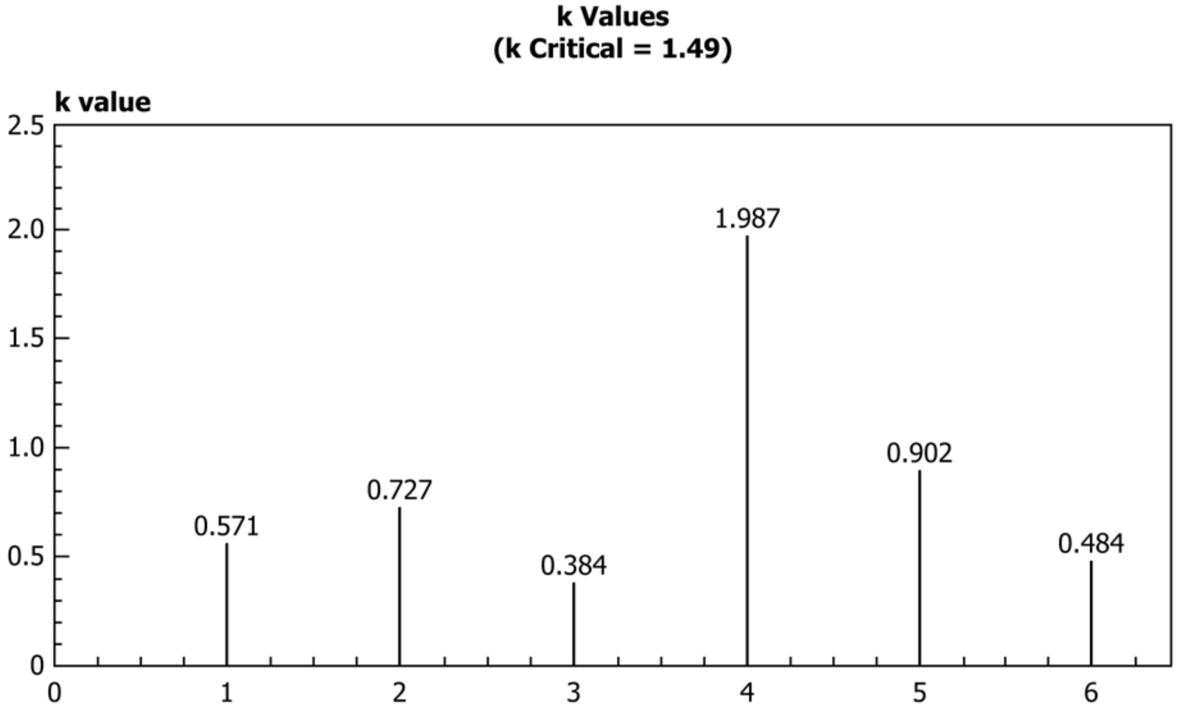

FIG. 12 *k* Values

TABLE 2 Precision Statistics

X[A]	S_x[B]	S_r[C]	S_R[D]	r[E]	R[F]
75 643	42 706	30 269	51 611	84 753	144 511

[A] X = average of the cell averages.
[B] S_x = standard deviation of cell averages.
[C] S_R = reproducibility standard deviation.
[D] S_r = repeatability standard deviation.
[E] r = 95 % repeatability limit.
[F] R = 95 % reproducibility limit.

APPENDIXES

(Nonmandatory Information)

X1. RATIONALE

X1.1 This test method is needed to aid in the development of a high quality material for use in load-bearing implant applications. The influence of coatings on the resulting fatigue behavior of the system must be viewed as a combination of the surface-roughening treatments required to apply the coating, the thermal effects of the coating process, and any other secondary treatments used. The purpose of this test method is to provide the following information: (*1*) the influence of the preceding processing steps and (*2*) the integrity of the coating and the coating/substrate interface.

X1.2 The tapered cantilever beam test sample will still have some stress concentrations at the transitions into and out of the tapered region. Care must also be exercised in the design of porous surfaces applied to the beam as part of the test program. With porous surfaces that could have a contribution to the structural strength of the beam, the cross section of the porous material should also be tapered to keep the stress in the tapered region constant.

X1.3 Both the static shear test and the shear fatigue test are not loaded in pure shear. Because of the thickness of the combined porous surface and adhesive layer, there will be some bending forces across the test interface. This makes the test a combined shear and bending test. This is the reason that the 19.05 mm diameter is required unless another diameter is specified for the test sample. The diameter of the test pieces could have an effect on the amount of bending force across the test interface. To keep data between labs and materials more comparable the 19.05 mm diameter sample can be demonstrated to be equivalent to the 19.05 mm diameter sample. Because the amount of bending across the test interface is not easily determined the test results are calculated as pure shear.

X1.4 According to composite beam theory the extreme fiber stress calculation used for any of the bending fatigue samples with a porous coating will result in some minor differences between a sample with a porous coating and one without a porous coating. The porous coating can actually carry some force in bending that could result in a decrease of the extreme fiber stress at the solid substrate. The extreme fiber stress at the substrate will decrease with increasing elastic modulus of the coating and increasing thickness of the coating. X2.1 outlines the classical mechanics calculations necessary for determining the stresses at all locations in the composite beam exemplified by a sample with a porous coating. For most test samples this can probably be ignored and normal beam calculations can be used without accounting for the porous coating.

X2. VALIDATION DATA FOR HYSOL 9514 from Endolab GmbH

X2.1 Endolab showed equivalency of the adhesive HYSOL 9514 to the recommended FM 1000 specified in this standard for shear testing. A total of five samples were statically shear tested using the method of this standard. Instead of coated samples a blasted surface was used as the test surface. A mean static shear strength of 50.54 MPa was determined for HYSOL 9514 adhesives in this test.

X3. COMPOSITE BEAM CALCULATIONS

X3.1 *Calculation of Stresses in a Porous Coated Cross Section*—The solid cross section is rectangular and the cross section of the porous coating attached to the solid surface is also retangular.

X3.2 The cross section has a thickness d_s, a width b_s, and an elastic modulus E_s. The porous cross section has a thickness d_p, a width b_p, and elastic modulus E_p.

X3.3 It is first necessary to determine the porous coated composite beam neutral axis using the method of Third Edition, Mechanics of Materials, Gere and Timoshenko (p. 302). To simplify the writing of the complex equation it will be written in two parts. The distance from the neutral axis to the external surface of the porous surface is h_p. The distance from neutral axis to the external surface of the solid is h_s. These values can be used to calculate the moments of inertia of the solid section I_s and the porous section I_p about that neutral axis.

$$Eq_1 = (E_p \cdot b_s \cdot b_p \cdot d_p) + \frac{(E_p \cdot b_p \cdot d_p^2)}{2} + \frac{(E_s \cdot b_s \cdot d_s^2)}{2}$$

$$Eq_2 = (E_s \cdot b_s \cdot d_s) + (E_p \cdot b_p \cdot d_p)$$

$$h_s = \frac{Eq_1}{Eq_2} \quad h_p = d_s + d_p - h_s$$

$$I_p = b_p \cdot \frac{d_p^3}{12} + b_p \cdot d_p \cdot \left(h_p - \frac{d_p}{2}\right)^2 \quad I_s = b_s \cdot \frac{d_s^3}{12} + b_s \cdot d_s \cdot \left(h_s - \frac{d_s}{3}\right)^2$$

X3.4 Knowing the effective moments of inertia of each composite beam section and the respective elastic modulii, it is possible to calculate the stress at any distance y from the neutral axis in either section of the composite beams using the following formulae.

$$stress_s = \frac{(M \cdot y \cdot E_s)}{(E_s \cdot I_s + E_p \cdot I_p)} \qquad stress_p = \frac{(M \cdot y \cdot E_p)}{(E_s \cdot I_s + E_p \cdot I_p)}$$

X3.5 In most cases the thickness of the porous section is much less than the thickness of the solid section, and the elastic modulus of the porous material is much less than the elastic modulus of the solid material. Often the assumption that the porous section has a uniform elastic modulus is probably not true or the elastic modulus is not known. These formulae can be used to determine if the solid section of the test part is thick enough that the porous portion of the composite beam can be ignored.