Designation: E2789 − 10 (Reapproved 2021)

Standard Guide for Fretting Fatigue Testing[1]

This standard is issued under the fixed designation E2789; 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 defines terminology and covers general requirements for conducting fretting fatigue tests and reporting the results. It describes the general types of fretting fatigue tests and provides some suggestions on developing and conducting fretting fatigue test programs.

1.2 Fretting fatigue tests are designed to determine the effects of mechanical and environmental parameters on the fretting fatigue behavior of metallic materials. This guide is not intended to establish preference of one apparatus or specimen design over others, but will establish guidelines for adherence in the design, calibration, and use of fretting fatigue apparatus and recommend the means to collect, record, and reporting of the data.

1.3 The number of cycles to form a fretting fatigue crack is dependent on both the material of the fatigue specimen and fretting pad, the geometry of contact between the two, and the method by which the loading and displacement are imposed. Similar to wear behavior of materials, it is important to consider fretting fatigue as a system response, instead of a material response. Because of this dependency on the configuration of the system, quantifiable comparisons of various material combinations should be based on tests using similar fretting fatigue configurations and material couples.

1.4 *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.*

1.5 *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
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
E1823 Terminology Relating to Fatigue and Fracture Testing
E1942 Guide for Evaluating Data Acquisition Systems Used in Cyclic Fatigue and Fracture Mechanics Testing
G15 Terminology Relating to Corrosion and Corrosion Testing (Withdrawn 2010)[3]
G40 Terminology Relating to Wear and Erosion
G190 Guide for Developing and Selecting Wear Tests (Withdrawn 2021)[3]

3. Terminology

3.1 Definitions and symbols used in this guide are in accordance with Terminology E1823. Relevant definitions from Terminology G15 or G40 are provided in 3.2. Additional definitions specific to this guide are provided in 3.3.

3.2 *Definitions:*

3.2.1 Terms from Terminologies G15 and G40.

3.2.2 *coefficient of friction (COF)*—The dimensionless ratio of the tangential force, Q, between two bodies to the normal force, P, pressing these bodies together when the two bodies are slipping with respect to each other, μ=Q/P.

3.2.2.1 *Discussion*—Under partial slip conditions, the ratio of the tangential force to the normal force is less than the COF. In addition, when COF is defined as the ratio of Q to P, the

[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.

Current edition approved Dec. 1, 2021. Published January 2022. Originally approved in 2010. Last previous edition approved in 2015 as E2789–10 (2015). DOI: 10.1520/E2789–10R21.

[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] The last approved version of this historical standard is referenced on www.astm.org.

measured COF is an average along the interface. In reality, the COF can vary along the interface. Hence, a local definition is often used, given by $\mu(x,y)=q(x,y)/p(x,y)$ where $q(x,y)$ is the shear traction distribution along the interface and $p(x,y)$ is the normal pressure distribution. The COF is often greater in the slip regions of a partial slip interface compared to the stick regions due to the disruptions in the surface caused by fretting. **G40**

3.2.3 *fretting*—Small amplitude oscillatory motion, usually tangential, between two solid surfaces in contact.

3.2.3.1 *Discussion*—The term fretting refers only to the nature of the motion without reference to the wear, corrosion, fatigue, or other damage that may occur. It is discouraged to use the term fretting to denote fretting corrosion or other forms of fretting wear due to the ambiguity that may arise. As the amplitude of fretting increases, the condition eventually becomes reciprocating sliding and the interaction should no longer be referred to as fretting.

3.2.4 *fretting corrosion*—The deterioration at the interface between contacting surfaces as the result of corrosion and slight oscillatory slip between the two surfaces. **G15**

3.2.5 *fretting wear*—Wear that occurs as the result of fretting action. **G40**

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *displacement amplitude*—The peak-to-peak relative displacement divided by two or total cycle displacement divided by four.

3.3.1.1 *Discussion*—The displacement amplitude is typically based on a remote reference location. Note that the definition of displacement amplitude in the context of fretting wear and tribosystems testing sometimes refers to the full peak-to-peak relative displacement, rather than the definition given here, which is consistent with the use of the term amplitude in Terminology E1823. Hence, whenever the term displacement amplitude is used, it should be clearly defined or a reference made to this guide.

3.3.2 *fretting damage*—The pits, scarring, disruptions and material transfer on the surface due to fretting.

3.3.2.1 *Discussion*—Cracks may be associated with the fretting damage, though in many cases they may not be present or be sufficiently small, such that the fatigue life is not significantly degraded. Hence, the disturbed appearance and level of roughness of the fretting damage cannot be reliably used to determine whether the fatigue life is reduced. In some cases the directionality of roughness, also called the surface texture, can be determined via profilometry methods. This texture may be correlated to the directionality of fretting and in some cases the characteristics of the texture can provide a useful screening metric for fretting damage.

3.3.3 *fretting fatigue*—The process of crack formation at a fretting damage site, progressive crack growth, possibly culminating in complete fracture, occurring in a material subjected to concomitantly fretting and fluctuating stresses and strains.

3.3.3.1 *Discussion*—*Fretting fatigue* is generally characterized by a sharp decrease in the fatigue life at the same stress level of a standard specimen, attributed to the shortened time to form a crack and the acceleration of the crack growth under the coupling of the fretting and bulk cyclic stresses and strains.

3.3.4 *fretting fatigue knockdown factor*—The reduction in fatigue strength due to the presence of fretting, defined as the difference in the fatigue limit and fretting fatigue limit divided by the fatigue limit.

3.3.4.1 *Discussion*—This knockdown factor may also be based on the fretting fatigue strength defined either as the stress level (maximum stress or stress amplitude for a given mean stress or stress ratio) for failure at a certain number of cycles or the stress level at which a percentage of the population would survive a certain number of cycles.

3.3.5 *fretting fatigue limit*—The limiting value of the median fatigue strength when fretting is present as the fatigue life becomes very large.

3.3.5.1 *Discussion*—The fretting fatigue limit strongly depends on the fretting conditions.

3.3.6 *fretting fatigue reduction factor*—The reduction in fatigue strength due to the presence of fretting, defined as the ratio of the fretting fatigue limit and fatigue limit.

3.3.6.1 *Discussion*—This reduction factor may also be based on the fretting fatigue strength defined either as the stress level (maximum stress or stress amplitude for a given mean stress or stress ratio) for failure at a certain number of cycles or the stress level at which a percentage of the population would survive a certain number of cycles.

3.3.7 *fretting fatigue damage threshold*—The combination of fretting fatigue loading conditions and number of fretting cycles that can be sustained before degradation of fatigue life is observed.

3.3.7.1 *Discussion*—The fretting fatigue loading conditions may include combinations of the normal force, the displacement amplitude, the tangential force amplitude, and the bulk fatigue loading. The concept of a fretting fatigue damage threshold is related to the development of an initial crack characterized with a maximum and range in stress intensity that exceeds the threshold value for crack growth. Generally, after the fretting fatigue damage threshold has been reached, removing the source of fretting, while maintaining the fatigue loading, in configurations where they can be separated, has minimal effect on the remaining life.

3.3.8 *gross slip*—The condition for which all points in contact experience relative slip over a complete cycle, as illustrated in Fig. 1.

3.3.9 *normal force*—Force normal to the contact interface.

3.3.9.1 *Discussion*—Due to the accumulation of debris within the contact or wear in the slip regions, this force may not remain constant but change during the test.

3.3.10 *normal pressure*—Resultant of the normal force divided by the contact area.

3.3.10.1 *Discussion*—To be considered an average only. The true distribution of pressure within the contact area depends on the exact profile and roughness of the contacting surfaces. Analytical or computational methods may be used to determine

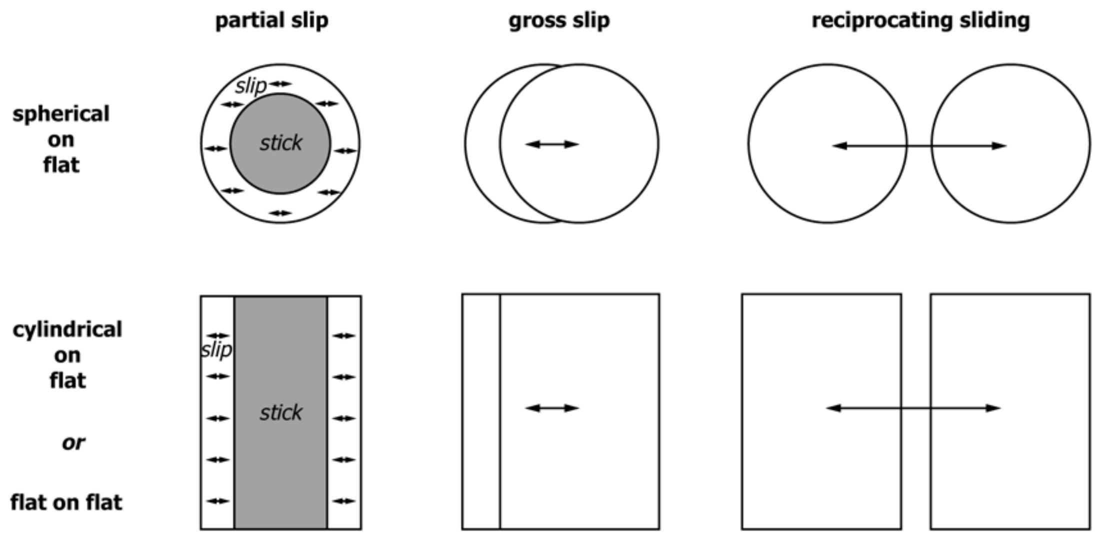

FIG. 1 Illustration of the Meanings of Slip and Reciprocating Sliding

this pressure; for example, see Ref. (**1**)[4]. Wear will cause the profiles of the contacting bodies to change during the test. If wear occurs, the size of the non-conforming contacts (for example, flat on cylindrical, cylindrical on cylindrical, sphere on flat, and so on) will typically increase.

3.3.11 *partial slip*—The condition for which only a portion of the interface of the contacting bodies experience relative slip over a complete cycle, as illustrated in Fig. 1.

3.3.12 *plain fatigue*—Often used to describe fatigue without presence of fretting.

3.3.13 *reciprocating sliding*—The condition when the contact area at the two extremes of the cycle do not overlap, as illustrated in Fig. 1.

3.3.13.1 *Discussion*—Under fretting conditions, at least a portion of the contact areas always overlap at the extremes of the cycle.

3.3.14 *relative slip*—The amount of tangential displacement between a point on the interface of one body and a point on the surface of the second body.

3.3.14.1 *Discussion*—The point on one of the bodies serves as a reference, which is often defined as the location when the two bodies first come into contact under application of the normal pressure at the interface. The relative slip may be defined as a local or remote reference. Fundamentally, a local measure is desired, however, experimentally a remote displacement is measured and in many times controlled.

3.3.15 *slip*—Local movement of surfaces in contact.

3.3.16 *tangential force*—Force acting parallel to the contact interface.

4. Significance and Use

4.1 Fretting fatigue tests are used to determine the effects of several fretting parameters on the fatigue lives of metallic materials. Some of these parameters include differing materials, relative displacement amplitudes, normal force at the fretting contact, alternating tangential force, the contact geometry, surface integrity parameters such as finish, and the environment. Comparative tests are used to determine the effectiveness of palliatives on the fatigue life of specimens with well-controlled boundary conditions so that the mechanics of the fretting fatigue test can be modeled. Generally, it is useful to compare the fretting fatigue response to plain fatigue to obtain knockdown or reduction factors from fretting fatigue. The results may be used as a guide in selecting material combinations, design stress levels, lubricants, and coatings to alleviate or eliminate fretting fatigue concerns in new or existing designs. However, due to the synergisms of fatigue, wear, and corrosion on the fretting fatigue parameters, extreme care should be exercised in the judgment to determine if the test conditions meet the design or system conditions.

4.2 For data to be comparable, reproducible, and correlated amongst laboratories and relevant to mimic fretting in an application, all parameters critical to the fretting fatigue life of the material in question will need to be replicated. Because alterations in environment, metallurgical properties, fretting loading (controlled forces and displacements), compliance of the test system, etc. can affect the response, no general guidelines exist to quantitatively ascertain what the effect will be on the specimen fretting fatigue life if a single parameter is varied. To assure test results can be correlated and reproduced, all material variables, testing information, physical procedures, and analytical procedures should be reported in a manner that is consistent with good current test practices.

4.3 Because of the wear phenomenon involved in fretting, idealized contact conditions from which the fretting contact area and pressure may be calculated exist only at the onset of the test. Although it is still possible to calculate an average fretting pressure using the initial contact area, the pressure within the contact area may vary considerably.

4.4 Results of the fretting fatigue tests may be suitable for application to design when the test conditions adequately mimic the design service conditions.

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

5. Background

5.1 *Interfacial Conditions:* When designing a test program to mimic the design service conditions, one must first identify whether the interface conditions are partial slip or gross slip. This will help determine which type of fretting fatigue test may be more relevant. In Fig. 2, a running condition fretting map is shown **(2)**. Two primary variables in fretting are the normal force and displacement amplitude. The latter is linearly related to the tangential force amplitude under partial slip conditions. On this map, three fretting regimes can be identified: the partial slip regime (PSR), the mixed fretting regime (MFR), and the gross slip regime (GSR). In the partial slip regime, part of the interface between the two bodies always remains in contact, hence the interface experiences partial slip each cycle from the beginning of the test. In the gross slip regime, the interface experiences gross slip each cycle. In the mixed fretting regime, the interface experiences gross slip in the early cycles and transitions to partial slip in the later cycles as the coefficient of friction increases due to fretting damage. The boundaries between these regimes are controlled by the other fretting parameters including surface finishes, environment, compliance of the test system, and so on.

5.2 Degradation due to fretting fatigue is most prevalent for fretting conditions located in the shaded region denoted as "cracking" on the material response fretting map shown in Fig. 2. When the displacement amplitude is large and well within the gross slip regime, fretting wear becomes the dominant mechanism. There is an overlap region where there is a competition between fretting fatigue and fretting wear. The boundary of the shaded region represents the fretting fatigue damage threshold. If the material response is in the fretting wear regime, a fretting wear test may be more relevant. See Guide G190 on developing and selecting wear tests.

5.3 It may be helpful to use fretting only tests (that is, fretting without addition of bulk fatigue loading) to help identify the damage regimes on the fretting maps. This approach is especially useful in situations where specimen material is limited, a large number of interfacial conditions are varied for design screening purposes, or the interfacial condition in actual components is sought.

6. Preparing a Test Program

6.1 *Contact Configuration*—Selection of the contact configuration and test apparatus depends to a large extent on the objective of the test program. Fretting contacts can generally be characterized by one of three configurations shown in Fig. 3. A point contact is generated using a spherical profile as the fretting pad. A crossed-cylinder arrangement also is classified as a point contact. Line contact is made using a cylindrical profile as the fretting pad. The advantage of these first two non-conforming contacts is the existence of closed-form Hertzian contact solutions that can be used to determine the tractions at the interface and hence the cyclic stresses in the bodies**(3)**. However, as wear increases beyond the first few cycles the Hertzian contact boundary conditions may no longer exist. The third contact configuration is the conforming area contact. With area contacts, the profile of the two bodies in the region of contact is generally flat. Since the fretting response may be sensitive to the geometry near the edge of contact, the transition radii at the edge of the pad, for example, as shown in Fig. 4, shall be measured and reported. If the loading is two-dimensional, the tractions at the interface and hence the cyclic stresses in the bodies can be determined knowing the

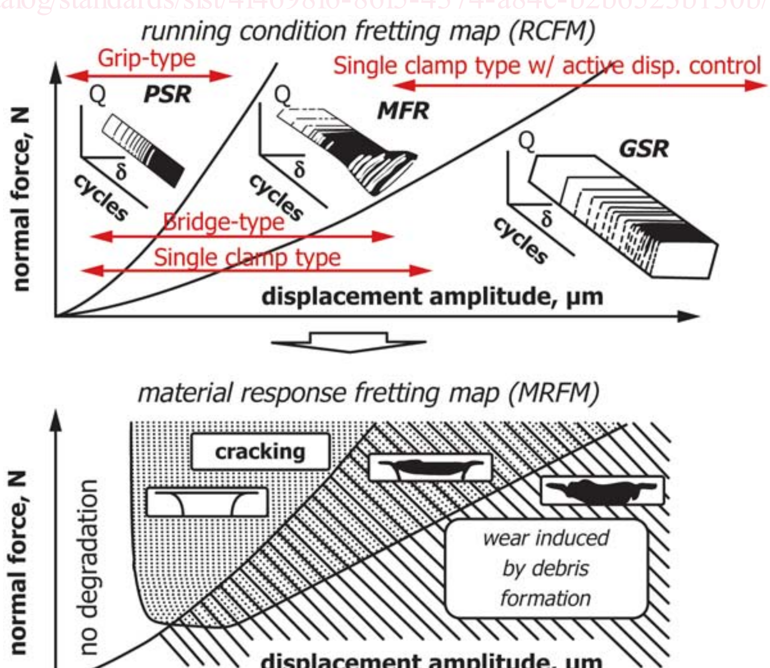

FIG. 2 Fretting Maps

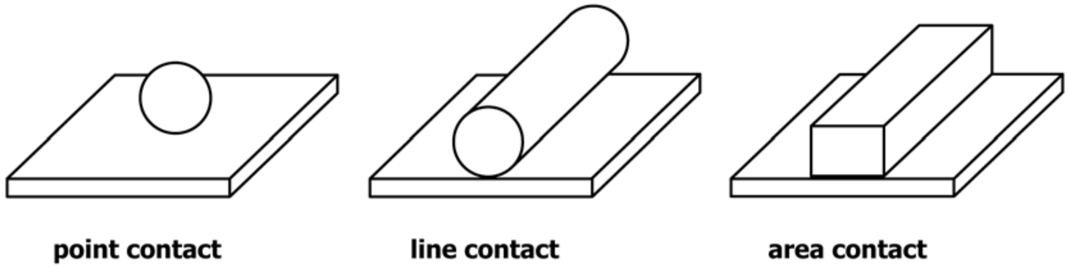

FIG. 3 Fretting Contact Configurations

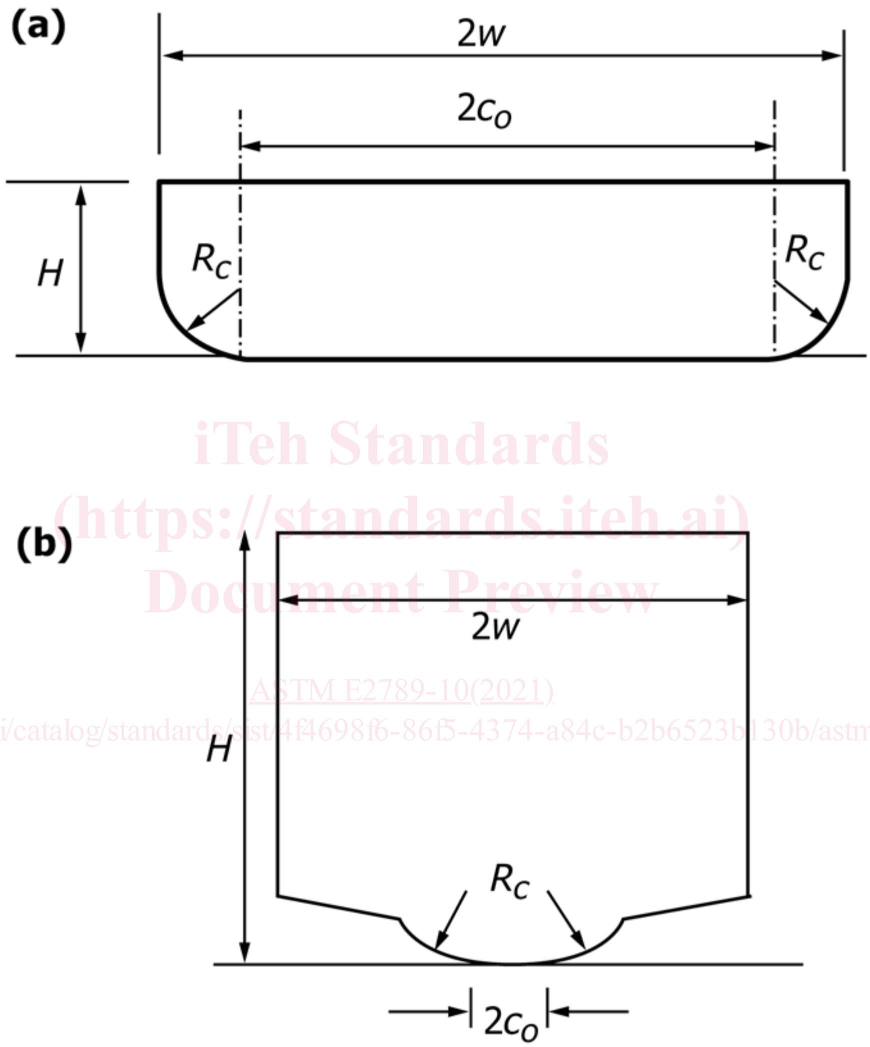

FIG. 4 Two Possible Fretting Pad Geometries with Area Contacts Showing Dimensions of Area Contact (c_o) and Bending Radii (R_c)

geometry of the pad (**4**). At the microscopic scale, the surfaces are not perfectly smooth, and hence the real tractions depend on the roughness (**3**).

6.1.1 It is recommended that in the case of line and area contacts, the edges of the two bodies perpendicular to the direction of fretting be aligned, as illustrated in Fig. 3, to minimize the concentration of pressure at this edge, unless the purpose of the test is to investigate this edge effect.

6.2 *Loading Configurations:*

6.2.1 Fretting fatigue tests are generally one of three types of loading configurations, shown in Fig. 5. Each loading configuration targets specific regimes as noted on the fretting map shown in Fig. 2. In this description, the fatigue specimen is designed to undergo axial loading similar to Practice E466. The merits of bending loading are discussed later. A description of the unique features of each configuration follows.

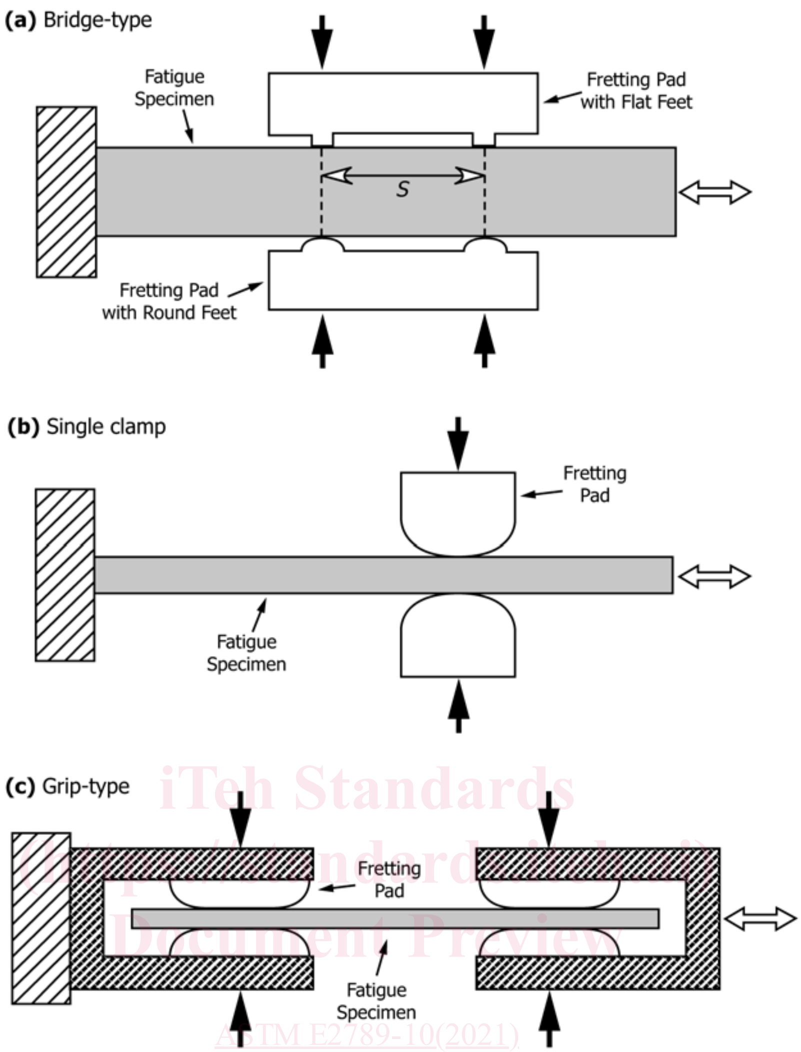

FIG. 5 Fretting Fatigue Test Configurations

6.2.2 *Bridge-type fretting fatigue test*—This test typically involves clamping two bridgeshaped fretting pads to the gage section of a fatigue specimen as shown in Fig. 5(a) (**5, 6**). The clamp and fretting pads are not attached to the frame and hence are free of any additional external loading. The displacement amplitude is generated when the fatigue specimen is cycled. The displacement amplitude depends on the differential between the cyclic strain in the fatigue specimen between the fretting pad feet and the cyclic strain induced in the fretting pads from the frictional force at the contacting interfaces. Therefore, the displacement amplitude depends on the elastic properties of the fatigue specimen and pads as well as the coefficient of friction at the contacting interface. For a given set of materials and coefficient of friction, the displacement amplitude can be adjusted by changing the span S between the contacting locations (that is, the feet of the fretting pads). Increasing the span increases the displacement amplitude. Hence, in this test configuration, the displacement amplitude is not directly controlled but is quasi-controlled through these other parameters.

6.2.2.1 One configuration of this type of test has been standardized by the Japan Society of Mechanical Engineers (JSME) (**6**). Presently, there are no ASTM standard test methods or standard practices for specific fretting fatigue test configurations.

6.2.2.2 The normal force is measured using an instrumented proving ring (**5**), small force transducer, or instrumented bolt. The fretting clamping apparatus should have low mass to reduce inertia loading if running the experiments at higher frequencies. The fretting test should be operated at test frequencies below this frequency-affected regime. The upper limit on test frequency may be determined by modal analysis or it may be determined by increasing the frequency until the tangential force – displacement hysteresis response significantly changes. Since displacement is proportional to axial force in the bridge-type fretting fatigue test configuration, assuming the fatigue specimen behavior is linear elastic, the hysteresis response can be seen by plotting tangential force (or fretting pad strain) versus axial force (or axial strain) in the fatigue specimen.

6.2.2.3 The tangential force transmitted to the pads is typically inferred from the displacement in the pad, which is usually measured with a strain gage. The tangential force is calibrated to the strain measured on the pad using a split specimen arrangement so that all of the force in the fatigue specimen is transmitted through the pad.

6.2.3 *Single clamp fretting fatigue test*—In this test illustrated in Fig. 5(b), in contrast to the bridge-type fretting fatigue test, there is a single fretting contact on each side of the fatigue specimen, though in some cases, a roller or other non-fretting material (for example, mica or TFE-fluorocarbon) is placed on one side to prevent or minimize fretting to one side of the fatigue specimen. The fretting loading device is attached to the test system frame in some manner. Hence, the displacement amplitude depends on the compliance of both the fretting chassis and fatigue specimen. There are two general configurations that allow for the generation of tangential forces that are in phase with the force applied to the fatigue specimen. One involves arms that are attached to the axial loading train at some point. The other configuration involves using a specially designed fretting chassis that is attached to the test frame to press fretting pads symmetrically about a fatigue specimen (**7-9**). The chassis is designed to be stiff axially yet compliant transversely so that little of the normal pressure loading is transmitted through the rigid frame of the fretting chassis. At least 98 % of the pressure should be transmitted to the fatigue specimen instead of the fretting chassis, verified by finite element analysis (**7**). In the latter configuration, the displacement amplitude is primarily controlled by the compliance of the fatigue specimen, which can be adjusted by changing the length and cross section of the fatigue specimen.

6.2.3.1 The normal force is applied by springs, bolts, weights hanging from cantilever beam (**10**), pneumatic, or hydraulic actuators. The method of normal force application should be actively controlled or have sufficient compliance such that the normal force remains approximately constant despite surface evolution due to wear or material transfer. To determine the tangential force, the axial force is measured in the loading train on both sides of the fretting site with the difference corresponding to the tangential force transmitted at the interface (**8**). The axial force is measured using force transducers or is determined from strain gages attached to the fatigue specimen sufficiently far from the fretting site at a location where the stress state is uniform in the specimen. The tangential force transmitted through the fretting apparatus can also be determined by either strain gages or force transducers strategically located on the fretting chassis (**9**).

6.2.3.2 Typically, the displacement amplitude depends on fretting specimen compliance. The displacement amplitude should be measured since it is not directly controlled.

6.2.3.3 A modification of this test arrangement includes active control of the fretting pad displacement (**9, 11**). This modification increases the magnitude of the displacement amplitudes that can be tested as shown on the fretting map in Fig. 2.

6.2.4 *Grip-type fretting fatigue test*—In this type of test, fretting fatigue occurs in the grip section as illustrated in Fig. 5(c). The fretting pads are typically flat with blending radii at the edges (**12**), though other contact configurations could be used. This fretting fatigue test is limited to partial slip conditions, since gross slip would result in slip out of the grips. The normal clamping force is typically measured by instrumented bolts or force transducers. The tangential force at the interface is simply the axial force applied in the test system. Fretting fatigue conditions may be generated at both ends of the fatigue specimen if desired, though the cross-section of one grip section may be larger so fretting is just promoted at the other grip section (**12**). A comparative study of the grip-type and single clamp fretting fatigue test configurations is provided in Ref. (**13**).

6.2.5 *Uniaxial vs. bending loading configuration*—Generally, uniaxial loading is preferred because the interface conditions can be better controlled and modeled (**7**). Under certain circumstances, a bending loading may be desirable. A bending loading has particular utility when evaluating surface treatments that induce compressive residual stresses when fatigue cracks could form at internal sites where the residual stresses are tensile. Bending loading may also be appropriate when attempting to better mimic applications that have a large bending component in the loading. A bending loading is acceptable as long as the boundary conditions and geometries between the boundaries are reported.

6.2.6 In a well-designed fretting fatigue test, the following should be controllable or monitored throughout the duration of the test: the mean and alternating forces on the fatigue specimen, the normal force applied to the fretting pads, the relative displacement of the two bodies, the alternating tangential force, and frequency of cycling.

6.2.6.1 The test equipment should have a means of monitoring the fatigue loading and the forces at the contact interface. Monitoring of the normal force at the contact interface can be accomplished through either a force transducer in-line with the normal force or using calibrated strain gages on the loading device. If the normal force is applied by means of a constant displacement method, such as a proving ring or bolt, care should be taken to continuously monitor the normal force due to the possibility of it changing as wear debris becomes entrapped within or is released from the contact area. If the normal force is not adjusted during the test, the evolution of this normal force should be reported. Monitoring of the axial forces in the fatigue specimen should be accomplished by means of a transducer in series with the fatigue specimen, calibrated and verified in accordance with Practice E4.

NOTE 1—If the test system is such that the forces seen by the fatigue specimen are influenced by the system dynamics (that is, massive grips and high frequency), a dynamic force verification of the axial force should be performed per Practice E467.

6.2.7 *Local vs. reference displacement*—Measured values of displacement do not represent the actual relative slip displacement at the interface because of compliance of the bodies between the displacement measurement location and contact interface. Hence, measured values of displacement amplitude are in reality reference values that depend on test method, geometries, contact configurations, etc. Wear scars and hysteresis loops are the best indicators of the slip condition and hence should be reported. The local response is typically determined through modeling (for example, finite element model).

6.2.7.1 Hence, it is critical to clearly report dimensions of the test configuration between locations where force and displacement measurements are made (that is, the boundary