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Overview

Introduction

With the present state of knowledge, the fretting fatigue problem is commonly approached empirically by testing the material/component under simulated conditions of contact and environments. The extreme difficulty in performing fretting fatigue testing manifests itself not only through the large number of process variables but also through their mutual interactions and the self-induced changes in the tribological system. The discrepancy among published data is, therefore, not surprising. The possibility and potential for improving the repeatability of test data do, however, exist with proper and comprehensive understanding of the sources of uncertainties.

Objectives

The main objectives of this symposium/publication are as follows:

1. Review the present state of knowledge and the current fretting fatigue testing practice.
2. Identify the areas of uncertainties in conducting fretting fatigue testing, including the design of the test specimens, as well as the measurement and control aspects.
3. Identify the measures that should be taken to improve the repeatability of test results and to minimize their dependence on the design of the test equipment.
4. Examine the future prospects for standardization, and identify the areas that warrant further research.

This book will be useful to tribologists, physicists, and mechanical engineers who are involved with fretting fatigue testing and those who are concerned with contact problems, particularly where fatigue and vibration are concerned, for example, in turbines, generators, aircraft, structures involving steel ropes, and so on. The paper presented by Hattori et al., for example, shows how problems have been overcome in the design of steam turbines. Vincent et al. and Vingsbo discussed the use of fretting maps for controlling the fretting fatigue damage in practice. Other papers show the effectiveness of certain preventative measures such as surface treatment and cathodic protection in marine environments. The papers presented in this publication cover the response of common-place materials, such as steel and aluminum, as well as the less conventional materials such as composites.

Overview of the Papers of the Symposium

This special technical publication contains 20 papers written by renowned authorities in this field. The opening keynote paper, presented by R. B. Waterhouse, provides a global overview of the problems of fretting fatigue testing and presents the author's perspective and views on the main issues that should be addressed in any attempt to standardize fretting fatigue testing. In addition, a total of four invited keynote papers were also presented by Vingsbo, Hoeppner, Hills, and Vincent to simulate and set the stage for focused and fruitful discussion during the symposium. The closing paper by Attia, the Chairman of the ASTM Task Group E9.08.02 on Fretting Fatigue Testing, examines the future prospects for standardization in relation to the current practice. The paper presents also the results of a survey in which the input was solicited from 65 active researchers in various parts of the world.

This special technical publication reflects the trends and testing philosophy in ten different countries and is, therefore, characterized by its international flavor. Apart from the opening and closing position papers, the papers of this symposium are grouped in five sections:

Fundamental Aspects of Fretting Fatigue Testing—Conceptual Framework

This section includes four papers that provide a conceptual framework for the mechanical and physical interactions associated with the fretting fatigue process and testing. Following a brief presentation of the historical evolution of the fretting fatigue testing, Hoeppner reviewed the mechanism of fretting fatigue and the contributions that have been made in understanding the crack nucleation and in characterizing the fretting fatigue damage. He underlined those parameters that can be considered as mechanism controlling and presented the recent developments in micromechanical modeling. The paper concluded with the recommendation for standards development and the identification of some areas that warrant further research.

Vincent, Berthier, and Godet applied their concept of "velocity accommodation" to the fretting process and showed that the relative displacement and velocity difference between the core of contacting solids are accommodated at different sites (the rubbing solids, their interface, or the surface screens) and according to different modes (elastic, rupture, shear, and rolling). Depending on the surface tensile stresses and whether adhesive welds break before crack initiation, it was indicated that the material responds to fretting in three different ways: no degradation, crack formation, and particle detachment. Since different material responses can be observed during a single test, the authors stressed the importance of constructing "fretting maps" to identify the material response to specific running conditions. To extend the velocity accommodation and fretting maps concepts to fretting fatigue testing and to overcome the classical problem of the dependence of the displacement amplitude on the body stress level, the authors proposed a new "fretting-static fatigue" testing method. This method, which is based on applying a constant body stress and controlling the slip amplitude independently, requires a set of fretting maps to be produced for different loads, slip amplitudes, and number of cycles. The authors proposed also a measure for the "severity" of the test, and outlined how the design engineer can use these maps to identify and avoid fretting fatigue failures. In this paper, some fundamental questions were raised, regarding the contact mechanics parameters that govern crack initiation/propagation, and the significance of the drop in the fatigue strength measured in fretting fatigue test machines. The latter issue was discussed in relation to the formation/retainment of wear debris, and the effect of the machine stiffness.

The subject of fretting maps, which define the effect of the process parameters on the extent of the stick, partial- and gross-slip regimes, was also discussed by Vingsbo. Using a simple model of surface asperities in elastic contact with a perfectly flat semi-infinite body under cyclic loading, the author concluded that surface fatigue is promoted by fretting under mixed stick-slip conditions, both in terms of cyclic stress concentrations and plastic deformation in the contact zone. The author's view on establishing fretting maps for a given tribo-system to control the fretting fatigue damage in practice is readily applicable to the design of a controlled fretting fatigue testing system.

Perhaps the most difficult problem to be encountered in developing standards for a controlled and well-defined fretting fatigue test is handling the large number of process variables. The popular list of variables, which was originally assembled by Collins in 1964, includes as many as 50 variables! In reviewing the stress models, which were successfully used to predict the fretting fatigue strength, Dobromirski argued that the vast majority of these variables, which are not explicitly included in the stress models, can be treated as "secondary" variables that influence the process through their effect on the "primary" variables. The latter is a short list of three variables, namely, the coefficient of friction, the displacement amplitude, and the contact pressure. The coefficient of friction was further singled out and identified as the main primary variable. By re-examining a large sample of available fretting wear/fatigue data, from this perspective, the author was able to use the coefficient of friction as a common denominator to explain the effect of various process parameters on the fretting fatigue test results. Beyond the obvious benefit of reducing the list of variables to a manageable and practical number, Dobromirski's analysis should be taken one step further to alert all of us that the time has come to treat the coefficient of friction as one of the parameters that should be measured in fretting fatigue testing. It will be noted throughout this book that the emphasis on the critical role of friction force is echoed by many others.

Fundamental Aspects of Fretting Fatigue Testing—Mechanics of Contact

This section includes four papers that deal with the theoretical aspects of the mechanics of contact, and the application of numerical techniques; for example, finite-element and boundary-element methods to calculate the contact stresses. Experimental verification, using the caustics method, is also presented. The authors maintained their focus on the main objectives of this symposium and presented their analysis in terms of two important issues: the design of the fretting pad/fatigue specimen and the method of applying the normal contact load.

The paper presented by Hills and Nowell is centered around the idea that specimen/pad geometry should be amenable to a well-defined stress field and fracture mechanics analysis. They highlighted the drawbacks associated with the flat-ended fretting pad; for example, the singularities in the contact stress distributions and the difficulty in defining the slip-stick zones. They recommended the adoption of a "cylindrical bridges against flat tensile specimens" configuration, since it allows changing the contact size while keeping constant normal load, as well as controlling the normal and tangential contact forces independently. The paper deals with some points of interest to those involved with the task of developing standards for fretting fatigue tests, namely, the contact size threshold phenomenon and the nature of the distribution of the coefficient of friction over the contact area.

Using the boundary element method, Sato studied the effects of clamping position (central versus edge clamping) as well as the bridge height on the magnitude and the distribution of the contact pressure at the specimen/bridge interface. The results of the plane-stress analysis of the bending fatigue problem were validated experimentally, using the method of caustics. The concept of "equivalent stress amplitude," as defined by Tresca's yield criterion, was proposed by the author for estimating the fretting fatigue strength. From the *S-N* fretting fatigue test results, it was established that the bridge height affects the fatigue life only under central clamping conditions (negative effect). The author was successful in interpreting these results in relation to the contact pressure amplitude, defined as half the difference between the compressive and tensile contact pressures at the outer edge of the contact area. The paper was concluded with the recommendation to use either central clamping when the bridge height-to-contact length H/L ratio is unity, or to use edge clamping for fretting fatigue tests with other H/L ratios. To improve the fretting fatigue strength, the author demonstrated a way of reducing the contact pressure amplitude through the machining of grooves in the fatigue specimen near the end of the bridge.

The application of the boundary element method for calculating the contact pressure distribution and the concept of controlling it through grooving and surface knurling were also discussed by Hattori, Nakamura, and Ishizuka. In this paper, the fretting fatigue limit was predicted using the fracture mechanics approach. These predictions were also verified experimentally. The paper addresses some interesting points in relation to the measurement and modeling of the effective stiffness of the contact interface. The example given in the paper for improving the fretting fatigue strength through optimization of the groove geometry (to counteract the negative notch effect with the positive effect associated with the rise in the threshold stress intensity range factor) provides a methodology for designing the configuration of fretting fatigue test specimens.

The effect of the average contact pressure on the fretting fatigue strength was further investigated experimentally by Nakazawa, Sumita, and Maruyama. The test results indicated that the relationship between the fretting fatigue life and the contact pressure is influenced by the stress amplitude. At low-stress amplitude (<20% of the 0.2% PS of high strength steel), this relationship is nonmonotonic and passes through a minimum and then a maximum before reaching a constant level. At high-stress amplitude (>40% of the 0.2% PS), the increase in the contact pressure leads to a continuous drop in the fretting fatigue life. The authors reported also the increase in the frictional stress amplitude with the increase in the contact pressure. For the steel used, it has been indicated that the crack initiation sites shift from the middle portion of the contact area to the outer edge as the contact pressure is increased. This observation is of a particular importance to fracture mechanics analysts who usually assume that cracks initiate at the contact edge.

Fretting Fatigue Testing—Methods and Equipment

In this section which includes five papers, the present state of the art in fretting fatigue testing is reviewed, and the relative merits of various test methods are evaluated. A few recommendations were made regarding the adoption of commercial equipment, proven techniques and experimental test rigs, as a starting point for standards development. Some interesting concepts and observations were also made, providing guidelines for conducting proper simulative tests.

The fretting fatigue testing and research activity at the Royal Aerospace Establishment (RAE) the U.K. was critically reviewed by Rayaprolu and Cook. Over the last 15 years, the test methods and test variables at RAE were progressively changing to satisfy specific requirements and objectives. Four stages or test series were identified by the authors to reflect such a change. The conventional fretting fatigue setup with a proving ring was used in the first test series to investigate the effects of the pad span, contact load and body loading type on the fatigue endurance. The second test series was motivated by the need for knowing the local stresses induced by fretting in order to apply fracture mechanics models. Here, the frictional force measurement was introduced. In the third stage, the experimental research effort was directed towards identifying the separate effects of the contact, frictional, and body loads on the fatigue process. Using a biaxial fatigue machine with phase linked actuators, a fourth series of tests is being currently undertaken to examine the effect of cyclic load variations on the cyclic frictional load, as well as crack initiation and propagation. The paper summarizes also the work related to fracture mechanics modeling at RAE. Recommendations for standard test setup, procedures, and future work were presented in the last two sections of the paper. To improve the fracture mechanics prediction capability, the effect of the contact parameters on crack initiation and growth, particularly with reference to initiation sites and angular and short crack growth, was identified as an important area for further research. It is worth noting that this recommendation is well founded by the observations made by Nakazawa et al.

The paper given by Lindley and Nix described the two fretting fatigue test methods used at the National Power Technology and Environmental Centre in the United Kingdom. These methods are similar to those used and recommended in the previous paper by Rayaprolu and Cook, namely, the proving ring and the biaxial test rigs. The advantages of the latter system were discussed in terms of controlling the contact load and the relative slip between the specimen and the pad, as well as applying variable amplitude loading. The paper describes also alternative fretting pad geometries and emphasizes the requirements for frictional force measurement during the test. The two approaches of fretting fatigue analysis, the *S-N* curve and the fracture mechanics modeling, were also reviewed.

For a proper simulative fretting fatigue testing, Ruiz, Wang, and Webb introduced the fatigue-fretting damage parameter (FFDP), as a measure of the severity of fretting fatigue damage. This parameter is a function of the tangential stress along the line of contact, the interface shear stress, and the relative slip and, therefore, includes the variables that control the initiation of fretting surface damage (wear) and the growth of the cracks. The main thrust of the paper is centered around the importance of getting the three components of the FFDP right in any test designed to reproduce the conditions prevailing in a real structural joint. The paper discussed further the issue of controlling these variables in three types of tests: biaxial, tension/compression, and 3-point bending tests. The authors pointed out the proper choice of the test method, depending on the ductility of the material tested.

The paper presented by Fischer, Grubisic, and Buxbaum deals with a very important and fundamental issue in fretting fatigue testing: the effect of load sequence. The experimental study carried out by the authors on the fretting fatigue behavior of nodular cast iron under constant amplitude and load spectrum (random sequence) throws the light on a few important findings. First, the common test practice of constant stress amplitude produces more reduction in the fretting fatigue strength because of higher slip amplitude and higher degree of "embedding." Second, the widely accepted notion of the negative effect of the contact pressure on the fretting fatigue strength (under constant stress amplitude) cannot be extended to the case in which the stress amplitude follows a random sequence. Third, the significant improvement in the fretting fatigue strength with residual compressive stresses, for example, due to shot peening, was not observed in plain fatigue testing under spectrum load. Although these conclusions cannot be generalized, at the moment, beyond the test conditions reported by the authors, they demonstrate the importance of proper simulation of the loading conditions encountered in practice and suggest the improved repeatability of the test results under random sequence loading, even when the contact pressure and residual stresses are not precisely controlled and defined.

Labedz's paper deals with the adaptation of commercially available servo-hydraulic testing machines and the use of a univeral test rig for fretting testing. The proposed test method is in harmony with Dobromirski's concept of primary/secondary variables and considers only five essential test variables. The author brings to our attention two test parameters that are usually ignored in fretting wear/fatigue testing: the contact temperature and the residual stresses. The effect of the latter was experimentally investigated to confirm its importance and to demonstrate the proposed test method.

Environmental and Surface Conditions

This section includes three papers that deal with the effect of surface residual stresses and the environmental conditions (for example, temperature, vapor content, and corrosivity) on the fretting fatigue test results. These papers point out the importance of monitoring and duplicating the environmental conditions and the state of stresses at the surface of the specimen. Some experimental techniques, for example, X-ray diffraction, scanning electron microscopy (SEM), atomic emission spectroscopy (AES), Mossbauer spectrometry, and electrochemical techniques were described.

The effects of the compressive residual stresses and the environmental temperature on the fretting fatigue test results were investigated by Mutoh, Satoh, and Tsumoda. Some considerations for testing and measuring frictional forces at elevated temperatures were discussed. The paper examines also the relationship between the coefficient of friction and the stress amplitude. It has been concluded that for the given test conditions, this relationship is unique regardless of the temperature and the surface residual stresses. This behavior was attributed to the insensitivity of the following mechanisms to surface and environmental conditions: oxidation (to temperature), and surface roughness and hardness (to shot peening).

The paper presented by Yunshu, Baoyu, and Weili focused on the effect of the environment on the debris structure and its tribological properties. Using surface analysis techniques, the authors concluded that if the environmental conditions promote the wear debris to act as an effective solid lubricant, the fretting fatigue strength will be partially restored, as in the case of blade steel fretted in vapor. They also concluded that the environmental effects become less important in the presence of compressive stresses.

The paper presented by Price and Taylor is concerned with two issues: the synergistic effect of the mechanical and electrochemical components of the fretting fatigue process and the application of electrochemical techniques to separate and evaluate the role of corrosion in tests run in aqueous environment. An experimental setup was developed to control the corrosivity of the medium and to identify the electrochemical dissolution process through the use of impressed cathodic protection. For the test conditions specified in the paper, the authors concluded that the electrochemical processes have the greatest influence on the fatigue life of high-strength low-alloy steel. The paper draws the attention to the requirement of assessing the contribution of the corrosion action in fretting fatigue testing, and provides a method for achieving that.

Nonconventional Materials and Test Methods

This section includes two papers that deal with nonconventional test configuration and materials. The fretting fatigue testing system developed by Cardou, Cloutier, St. Louis, and Leblond to test overhead electrical conductors is based on exciting the conductor at the span midpoint, with a controlled cyclic deflexion. The concept of primary and secondary test variables was independently applied in this paper, and two test methods were followed, namely the wire fracture time sequence and fracture location analysis.

In the paper presented by Jacobs, Friedrich, and Schulte, a special test setup was developed to study the mechanism of fretting fatigue of carbon fiber reinforced expoxy (CFRE) laminates. In contrast to the observation made by Lindley and Nix, the authors found that the fretting fatigue life of CFRE is significantly affected by the fretting pad material. This was contributed to the mechanism of interaction between fretting wear damage and fatigue, which is also sensitive to the contact pressure and the hardness of the fretting pad material. The authors established that the fretting fatigue mechanism of fiber reinforced polymers is characterized by multiple matrix cracking along the fibers and, therefore, the available fracture mechanics models are not applicable to these materials. A theoretical model for the "fretting fatigue load versus number of cycles to failure" and the "specific pseudo-wear rate" was developed and verified experimentally.

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This publication is only one aspect of the symposium. The sessions and the discussions contribute greatly to the mission of the symposium. The effort of the co-chairmen of the sessions is acknowledged and appreciated. The editors are thankful to the attendees of the symposium for the interesting points and useful comments they made during the discussions that followed the paper presentaion, and during the panel discussion session. Their enthusiasm to follow up this symposium with similar conferences in the future is appreciated and well taken. The editors hope that those concerned with the subject of fretting fatigue will find this publication useful and stimulating.

M. Helmi Attia

Ontario Hydro Research Division, Toronto, Ontario, Canada; symposium chairman and editor.

R. B. Waterhouse

Department of Materials, Engineering and Materials Design, University of Nottingham; symposium chairman and editor.