Monday, August 20, 2007

Tuesday, August 21, 2007

Wednesday, August 22, 2007

An Opening Overview Talk

Monday AM — Room: Rackham Amphitheatre
August 20, 2007 — Location: Rackham Center

8:30 AM Welcome Comments

8:40 AM Keynote
Review and Prospects for Current Studies on Very High Cycle Fatigue of Metallic Materials for Machine Structural Use: *Tatsuo Sakai*[1]; [1]Ritsumeikan University

In recent years, economic and environmental considerations have increased the need to safely extend the service life of energy conversion and transportation systems beyond their original design life and provided the impetus to design new systems/components with fatigue lifetimes significantly greater than 107. Thus, the fatigue behavior of structural materials in the very high cycle regime of 10^9-10^{10} cycles has become an important and active area of research. In this lecture, a review of the current studies in this area performed by many researchers all over the world was attempted in order to provide a milestone in the history of the research on fatigue behavior of the metallic materials in the very high cycle regime.

Microstructure and Initiation Mechanisms I

Monday AM — Room: Rackham Amphitheatre
August 20, 2007 — Location: Rackham Center

Session Chairs: Hael Mughrabi, University of Erlangen; Brian Laird, University of Kansas

9:10 AM Keynote
PSB Threshold and Fatigue Limit of Polycrystalline Copper in the VHCF-Regime: *Stefanie Stanzl-Tschegg*[1]; Bernd Schönbauer[1]; [1]Universität für Bodenkultur Wien

Measurements on the existence of a fatigue limit as well as formation of PSBs have been performed on polycrystalline copper up to 1011 cycles with the ultrasonic fatigue testing technique. The resulting Manson-Coffin and Wöhler (S-N) plot may be approached by two lines with different slope, showing that a fatigue limit does not exist below at least ~10^{10} cycles. PSBs were detected at values *below* the expected PSB threshold reported in the literature and in former own studies. They were identified after loading at high enough number of cycles (in the VHCF range), polishing and reloading during 2x106 cycles. Thus the formation of PSBs seems to be not only determined by the loading amplitudes, but also number of cycles. Measurement of the plastic strains at 19 kHz and 20 Hz showed that a frequency (strain rate) effect exists, resulting in essentially lower plastic strain amplitudes at 19 kHz and thus higher stress amplitudes at comparable total strain amplitudes than at 20 Hz loading.

9:40 AM Invited
The Effect of a Cluster of Similarly Oriented Grains (a Supergrain) on Fatigue Crack Initiation Characteristics of Clean Materials: *David Davidson*[1]; [1]Southwest Research Institute

Clusters of grains having similar crystallographic orientation (supergrains) have been discovered in Waspaloy, Ti-6Al-4V, and steels. Supergrains may be considered as a previously unrecognized type of fatigue-related defect in extremely clean materials because they constitute a nonuniformity in an otherwise uniform and random grain structure. A simple model for the Stress (S) vs. Cycles to crack initiation (Ni) curve has been devised to illustrate and explore the effects of supergrains on the S-N curve and very high cycle fatigue limit. The possibility of detecting supergrains is also explored.

10:00 AM
Role of Pre-Strain Effects on the Fatigue Behaviour of Nickel-Base Alloys in the VHCF-Range: *Christian Stoecker*[1]; Martina Zimmermann[1]; Hans-Juergen Christ[1]; [1]University of Siegen

Most manufacturing processes of metallic components lead to plastic deformation in the material and hence cause pre-strain effects. The plastic pre-deformation strongly affects the initial microstructure of the material considered. Polycrystalline nickel-base alloys such as Nimonic 75 and Nimonic 80A, which were applied in this study, exhibit planar or wavy dislocation arrangements depending on the dominant strengthening mechanism (solid-solution or precipitation hardening) but also on the pre-strain history. By varying the heat-treatment conditions of the precipitation-hardened alloy (e.g., establishing the peak-aged and the overaged condition) a systematic adjustment of different microstructures, which were characterized by transmission electron microscopy, was carried out. Furthermore, possible grain size effects as well as the influence of surface roughness (by comparing mechanically and electro-chemically polished samples) were analysed. The results are reported and discussed in terms of the various contributions to the damage evolution during fatigue loading at constant load amplitudes in the VHCF-range.

10:20 AM
The Role of Microstructure on Fatigue Lifetime Variability in an $\alpha + \beta$ Ti-Alloy: *Christopher Szczepanski*[1]; Sushant Jha[2]; James Larsen[3]; J. Jones[1]; [1]University of Michigan; [2]Universal Technology Corporation; [3]United States Air Force

Ultrasonic fatigue has been employed as a technique to characterize the fatigue behavior of Ti-6%Al-2%Sn-4%Zr-6%Mo in the very high cycle regime. The microstructure is a two-phase structure with primary a grains in a transformed β matrix. Primary a grains produce a faceted morphology upon failure near the site of fatigue crack initiation. The microstructure near the site of fatigue crack initiation has been examined using orientation imaging microscopy (OIM), which indicates that a texture suited for basal and prismatic slip exists near the site of fatigue crack initiation. Clusters of primary alpha grains with similar orientation have been found just below the crack initiation site in some samples. The results of an analysis of metallographic sections will be presented to establish the relationship between the number density of these microstructural inhomogeneities and fatigue lifetime variability.

10:40 AM Networking Break and Poster Viewing

11:10 AM
Relating Gigacycle Fatigue to Other Methods in Evaluating the Inclusion Distribution of a H13 Tool Steel: *Jens Ekengren*[1]; Vitaliy Kazymyrovych[1]; Christer Burman[1]; Jens Bergström[1]; [1]Karlstad University

Inclusions play a crucial role for the fatigue properties of high strength steel, but to find the largest inclusions by microscopy measurements large areas have to be examined. In this project ultrasonic gigacycle fatigue testing has been used to find large inclusions in an H13 tool steel. The inclusions have been examined in SEM and their size distribution modeled using methods from extreme value statistics. The inclusion distribution obtained from the fatigue crack surfaces is compared to the corresponding staircase fatigue data via the Murakami √Area model and to distributions acquired by microscopy study of cross sections as well as ultrasound immersion tank measurements. It is shown that the fatigue method more effectively finds large inclusions than the other methods. It is also shown that the correlation between predictions of inclusion sizes by the √Area model from stress levels and fatigue initiating inclusions is weak for this material.

11:30 AM

S-N Curve Characteristic of Bearing Steel under Axial Loading Condition in Very High Cycle Fatigue Regime: *Kazuaki Shiozawa*[1]; Takayuki Hasegawa[1]; Liantao Lu[2]; [1]University of Toyama; [2]Southwest Jiaotong University

It has been observed under rotary bending fatigue to show a stepwise *S-N* curve in high strength steels. This behavior is caused by the transition of fracture mode from surface-induced fracture to subsurface one. Aim of this study is to clarify the *S-N* characteristic under an axial loading fatigue in very high cycle fatigue regime. In order to investigate the mean-stress effects, fatigue tests were carried out in air at room temperature under three applied stress ratios of -1, 0 and 0.5 using a hour-glass shaped specimen of high carbon-chromium bearing steel. From the results, *S-N* curve showed a smooth and continuous shape under three testing conditions in spite of the occurrence on interior inclusion induced fracture in high cycle fatigue regime. Detail discussion for fatigue fracture behavior was made through the observation of fracture surface and from point in view of the fracture mechanics.

11:50 AM

Surface Roughening and Fatigue Behavior of Pure Aluminum with Various Grain Size in the VHCF Regime: *Heinz Werner Höppel*[1]; Lilia Saitova[1]; Mathias Göken[1]; [1]Institute General Materials Properties

Investigations of the fatigue behaviour of pure aluminium have been carried out in the very high cycle fatigue (VHCF) regime up to 5108 cycles. The development of the surface roughening was investigated with light, scanning electron and atomic force microscopy, from which damage mechanisms and failure criteria were derived. Commercially pure aluminium with an average grain size of 350 nm obtained by equal channel angular pressing (ECAP) revealed improved fatigue characteristics in comparison with conventional aluminium. Furthermore, ultrafine-grained (UFG) Al shows insignificant surface roughness whereas in the case of conventional grained (CG) Al well developed extrusions and intrusions can be observed even after cyclic deformation at stress amplitudes lower than the PSB threshold stress.

12:10 PM

Observation of Inclusions and Defects in Steels by Micro Computed-Tomography Using Ultrabright Synchrotron Radiation: *Yoshikazu Nakai*[1]; Daiki Shiozawa[1]; Yasushi Morikage[2]; Takayuki Kurimura[3]; Hiroshi Tanaka[1]; Hideki Okado[4]; Takuya Miyashita[5]; [1]Kobe University; [2]JFE Steel Corporation; [3]Mitsubishi Heavy Industries, Ltd.; [4]Kawasaki Heavy Industries Ltd.; [5]New Industry Research Organization

In the present study, an ultrabright synchrotron radiation X-ray was applied to the imaging of subsurface inclusions and cracks. To obtain the basic data for the measurement, the penetration depth of the synchrotron radiation wave in free-cutting steels was examined. The maximum depth of the transmitted wave was 600 μm at the beam energy of 25 keV. To measure the size and shape of inclusions and cracks, X-ray micro computed-tomography using synchrotron radiation (SR-μCT) was employed. By comparing the image of free-cutting steels with inclusions with that of carbon steel, we showed that the microstructures observed by SR-μCT were inclusions. This method was also applied to the detection of small cracks that were initiated either in torsion fatigue tests of high-strength steel or fretting fatigue tests of stainless steel. Small cracks that were initiated in fatigue tests and whose depth was about 10 μm were detectable by the SR-ìCT.

Microstructure and Initiation Mechanisms II

Monday PM — Room: Rackham Amphitheatre
August 20, 2007 — Location: Rackham Center

Session Chairs: Tatsuo Sakai, Ritsumeikan University; Claude Bathias, CNAM/ITMA

2:00 PM Keynote

Fatigue Damage Evolution in Ductile Single-Phase Face-Centred Cubic Metals in the UHCF-Regime: *Hael Mughrabi*[1]; Stefanie Stanzl-Tschegg[2]; [1]University of Erlangen; [2]Universität für Bodenkultur Wien, University of Natural Resources and Applied Life

An attempt is made to summarize the fatigue behaviour of ductile pure single-phase face-centred cubic metals (and alloys) with emphasis on the Ultrahigh Cycle Fatigue range. Based on reports in the literature, on earlier models and on recent experimental results, it is proposed that surface fatigue damage can develop at loading amplitudes below the traditional fatigue limit after a very high number of cycles as a consequence of the accumulated effect of a remaining slight cyclic slip irreversibility. It is proposed that this fatigue damage occurs in the form of persistent slip bands (PSBs) which form at sites of local stress concentration and can lead to the initiation of stage I cracks. Under the assumption that these cracks can subsequently propagate and cause failure, a multistage fatigue life diagram is proposed. The currently available experimental evidence related to these issues is reviewed. In this context, a more detailed discussion of the PSB-thresholds and the stress and strain fatigue limits than in earlier work is presented.

2:30 PM Keynote

Initiation in the Gigacycle Fatigue Regime: *Claude Bathias*[1]; Paul Paris[2]; [1]CNAM/ITMA; [2]Washington University

SEM observations have shown that initiation in the gigacycle fatigue is often related to defect and flaws located beneath the surface, according the probability to find a defect. P. C. Paris and al. have developed an estimating model for sub-surface and internal initiations. C. Bathias and al. have developed an experimental approach to study the internal initiation using the thermal dissipation during the test. The conclusion of this work emphasizes the role of micro-plasticity around the defect in gigacycle fatigue and explains the formation of fish eye in terms of short crack initiation.

3:00 PM

Competing Failure Modes in Fatigue and the Consequent S-N Curve Shapes: *K. S. Ravi Chandran*[1]; Gerald Cashman[2]; [1]University of Utah; [2]GE Aviation

It has recently been discovered that competing fatigue failure modes lead to two separate S-N curves, one for surface-initiated cracks and the other for interior-initiated cracks. The competing failure modes and the associated two different fatigue life distributions occur in high strength materials that either have sparsely populated defects or processed to minimize the inclusion content. Typically, there exists a shorter life distribution that is associated with surface-initiated failures. The longer life distribution generally occurs due to internal-initiation cracks. There can be a complete separation of the two failure distributions or they can dominate at high and low stress ranges with a discontinuity in the mid stress range. Examples of competing failures in titanium alloys, nickel-base alloys and steels are presented. We illustrate the metallurgical and environmental conditions triggering this type of behavior. The competing modes phenomenon requires a new paradigm in material and fatigue life considerations.

3:20 PM

Study of Fatigue Crack Growth in Gigacycle Fatigue Domain by Thermal Analysis during the Tests: *D. Wagner*[1]; N. Ranc[1]; C. Bathias[1]; [1]Université Paris X - Nanterre

Some materials display a fatigue limit, but most others do not exhibit this response, and may crack up to 10^9 cycles. In this cycle domain, the initiation of the crack may be subsurface on a defect (inclusion, porosity...).To improve quality materials, it is necessary to understand why they can fail at 10^9 cycles under small elastic loading and why the initiation may be interior. In this paper, the study of the thermal dissipation during fatigue tests was carried out on different materials (steels and aluminium alloys). Tests were performed at ambient temperature using a piezoelectric fatigue system (20 kHz). The temperature field was measured on the surface of the specimen, by means of an infrared pyrometer. At the first time, it was observed that the temperature increased just at the beginning of the test, which is correspondent to the thermal dissipation in the specimen. At the crack initiation, the surface temperature suddenly increases, which allows determining the number of cycles at the crack initiation and the number of cycles devoted to the fatigue crack propagation. In the gigacycle fatigue domain, more than 97% of the total life is devoted to the initiation of the crack. In the case of a fish eye type propagation, the experimental data, issued from the thermal analysis, on the number of cycles during crack growth are in good agreement with the number of cycles calculated by Paris' model in the gigacycle fatigue range. This confirms that the propagation phase is very low in the gigacycle fatigue range. This study deals with steels and aluminium alloys. Thus, the study of the thermal dissipation during the test appears a promising method to improve the understanding of the damage and failure mechanism in fatigue and to determine the number of cycles at initiation.

3:40 PM

Very High Cycle Fatigue Behavior of the Steel with Carbide-Free Bainite/ Martensite Complex Microstructure: *Bingzhe Bai*[1]; Xuexia Xu[1]; Yang Yu[1]; Wenlong Cui[1]; Jialin Gu[1]; [1]Tsinghua University

The fatigue behavior of a novel high strength steel with microstructure of carbide-free bainite/martensite (CFB/M) multiphase and outstanding combination of strength and toughness was studied. Fatigue tests were carried out by ultrasonic fatigue testing equipment at a frequency of 20 kHz. The fatigue crack propagation rate, da/d_N, and fatigue threshold value, ΔK_{th}, were measured using Compact-Tensile specimens. Results show that there is no horizontal part in the S-N curve. Fatigue fracture still occurs when the life of specimen exceeds 10^7 cycles. Based on the observation of fracture surface, it is found that the originations of the fatigue crack tend to locate at the interior of the specimen as fatigue cycle exceeds 10^7. For many specimens of CFB/M steel, the originations of fatigue crack are not induced by inclusions, but by some kind of "soft structure". The fatigue limit of some specimens whose life is over 10^8 cycles is more than 700MPa, which is about 50% of its tensile strength. The steel also has higher fatigue threshold value, βK_{th}, and lower fatigue crack propagation rate, da/d_N, which probably originates from special CFB/M microstructure and advanced closure resistance to the fatigue crack tip.

4:00 PM Networking Break and Poster Viewing

4:20 PM

Gigacycle Fatigue of Precipitation Hardening Aluminum Alloys: T. Li[1]; M.R. Sriraman[1]; C. Wang[1]; *Q.Y. Wang*[1]; [1]Sichuan University

Aluminum alloys of the precipitation hardening type are widely used in automotive and aerospace applications. These are mostly subject to cyclic loading, sometimes involving high frequency vibrations, and are usually required to operate over a long period of life. It therefore becomes important to understand their very high cycle fatigue characteristics. The present paper concerns investigations on long life fatigue of AA7075-T6, AA2024-T3, and AA6061-T6. Push-pull fatigue testing was conducted in air at room temperature on hourglass specimens under completely reversed loading conditions (R = -1). The results reveal that failure in all the Al-alloys takes place even in the gigacycle range, with the fracture surfaces containing significant number of fatigue voids and/or facets. Fatigue experiments to such large number of cycles have been practically feasible using the ultrasonic fatigue testing procedure, which accelerates the testing time manifold vis-à-vis conventional testing method.

4:40 PM

Crack Initiation Mechanisms and Fatigue Lifetime of AISI 420 Steel under Constant and Variable Loading: *Bernhard Zettl*[1]; Stefanie Stanzl-Tschegg[1]; Herwig Mayer[1]; [1]Universität für Bodenkultur Wien

Ultrasonic fatigue tests are performed with AISI 420 steel up to 10^{10} load cycles. The material is tested in hardened and tempered condition and does not show a fatigue limit in S-N tests. Different crack initiating mechanisms are found, depending on the numbers of cycles to failure. At lifetimes below approximately 10^7 load cycles, crack initiation is preferentially at surface inclusions. In the regime from about 10^7 to 10^9 cycles to failure, cracks initiate at interior inclusions. When specimens fail at higher numbers of cycles (between 10^9 and 10^{10} cycles), cracks initiate at the surface and no inclusions are found. Two-step variable amplitude tests are performed in the VHCF regime. In contrast to the constant amplitude loading, crack initiation at interior inclusions was found in all tests, and specimens failed at low damage sums.

5:00 PM

Strength Level Dependence of Very High Cycle Fatigue Property in Interior Inclusion-Induced Fracture for Bearing Steel in Rotating Bending: *Tatsuo Sakai*[1]; Noriyasu Oguma[2]; Hisashi Harada[2]; [1]Ritsumeikan University; [2]JTEKT Corporation

In order to clarify the strength level dependence of the fatigue behavior in the long-life regime, rotating bending fatigue tests were carried out on bearing steels tempered at three different temperatures. Fatigue limit in the mode of surface induced fracture tended to decrease with a decrease of the specimen hardness. But, the fatigue life in the interior inclusion-induced fracture was improved as the hardness was decreased. Based on SEM observations of the fracture surface, characteristic rough surface of fine granular area (FGA) was found in the vicinity around the interior inclusion. Formation mechanism of this FGA was discussed from microscopic observations by TEM and X-ray diffraction patterns. Thus it was finally found that the martensite-lath was restructured into a number of microscopic subgrains and the area of FGA was caused by separation of the boundaries of these subgrains.

5:20 PM

Very High Cycle Fatigue of Railway Wheel Steels: Vadim Wagner[1]; B. Ebel-Wolf[1]; Frank Walther[1]; *Dietmar Eifler*[1]; [1]University of Kaiserslautern, Institute of Materials Science and Engineering

The fatigue behavior of railway wheel steels has been investigated in the Very High Cycle Fatigue regime until $2 \cdot 10^8$ cycles under stress-controlled fully reversed axial loading at a frequency of 200 Hz at room temperature. Specimens machined from original wheels of SAE 1050 widely used in Germany for high-speed passenger traffic exhibit a distinct change in the slope of the S-N (Woehler) curve at about $2 \cdot 10^6$ cycles. Temperature and electrical resistance of the individual specimens are directly influenced by deformation-induced changes of the microstructure and are qualified to characterize the actual fatigue state in detail, even at very high test frequencies. On the basis of Morrow, Coffin-Manson and Basquin equations, a physically based lifetime calculation .PHYBAL. was developed. The S-N curve calculated on the basis of temperature and electrical resistance data measured after 10^4 cycles, corresponding to a test running time of only 50 seconds, matches well with the experimental S-N data. Crack initiation was observed at the specimen surface as well as in the bulk.

5:40 PM
Crack Initiation and Propagation in a Duplex Stainless Steel during HCF and VHCF Loading: *Helge Knobbe*[1]; Ulrich Krupp[2]; Philipp Köster[1]; Hans-Jürgen Christ[1]; Enis Cherif[3]; Igor Altenberger[3]; [1]Universität Siegen; [2]FH Osnabrück - University of Applied Sciences; [3]Universität Kassel

The present study is focused on the crack initiation and propagation behaviour of short cracks during HCF and VHCF loading in austenitic-ferritic duplex stainless steel. Surface crack initiation is observed in the case of HCF loading, while a transition to subsurface crack initiation is possible during VHCF loading. Fatigue experiments have been carried out with ultrasonic as well as with servohydraulic testing systems in the HCF and VHCF regime. Experimental data, such as grain orientation, measured with automated EBSD, crack initiation sites and crack-propagation rates provide the baseline for the development and verification of a mechanism-based fatigue-damage simulation. The simulation is based on the boundary-element method and takes the local microstructural conditions into account. The barrier effect of grain/phase boundaries is considered by using Voronoi cells as a virtual microstructure. The results are discussed with the focus on special features of fatigue-crack propagation in the HCF and VHCF regime.

Poster Session

Monday, 8:30-10:00 PM — Room: Rackham Assembly Hall
August 20, 2007 — Location: Rackham Center

Advanced Apparatus

The following abstract was moved to page 19 in the Recent Advances in Apparatus and Instrumentation session at 10:00 AM

A New High Speed (150 Hz) Rotating Bending Fatigue Test Machine: *Gonzalo Dominguez*[1]; Mauricio Guzman-Tapia[1]; [1]University of Michoacan

A new machine to perform rotating bending fatigue tests at high speed (150 Hz) is presented in this work. A general description of this machine is developed concerning its design and operation, and regarding the capacity to attaint the very high cycle fatigue regime. To carry out tests at very high number of cycles, it is necessary to estimate the magnitude and to know the localization of highest strain and stress zones associated with crack initiation and fatigue failure. Influence of the parameters: applied load, rotating speed and geometry of the specimen on rotating bending fatigue are obtained by simulation with the aid of Visual-Nastran software. Finally, tests on the AISI-SAE 1018 steel are performed using this machine, the results are shown and discussed according the evolution of fatigue life and the observed fatigue failure origin.

Influence of Notches and Surface Conditions

In-Service Very-High-Cycle-Fatigue of Titanium Compressor Blades of Aircraft Engines: *Andrey Shanyavskiy*[1]; A. Potapenko[1]; [1]State Center of Civil Aviation Flight Safety

Compressor blades of titanium alloys VT3-1 and VT8 were investigated. Their in-service fatigue cracking had initiation under the surface in area of Very-High-Cycle-Fatigue. Blades of titanium alloy VT3-1 had fatigue cracking because the contact by the blade-shelves was loss as a result of intensive wearing out. Blades of titanium alloy VT8 had crack initiation under the surface of the blade-shelves because of heterogeneities of the transition area between fused material CT4 and main material VT8. The fused material CT4 used for repaired blades to increase size of wearied out surface of the blade-shelf. The paper includes a discussion of discovered fatigue fracture patterns and calculated stress levels for both materials.

Optimization of C/D Ratio of Adjacent Pre-Stressed Fastener Holes in HCF Using Finite Element Analysis: *Shanmukha Nagaraj*[1]; [1]Rashtreeya Vidyalaya College of Engineering

Pre-stressing is the process of introducing residual compressive stress zone around fastener hole which minimizes adverse effects of cyclic tensile stresses and retards the growth of fatigue cracks originating from the material flaws or surface imperfections. Present investigation is aimed at optimizing the inter hole distances between two adjacent cold expanded holes. The specimen subjected to HCF on a fatigue testing machine is modeled as a thick cylinder and the equations are derived for the radial stress. Graphs for these equations are plotted in MATLAB. A finite element analysis is carried out using ANSYS. The objective was to study the stress patterns in the vicinity of the holes and arrive at an approximate value of c/d. The stress patterns obtained from the analytical and FEA methods were found to be in agreeable comparison and this is a proof of the correctness of the approach.

Process Optimization for Pre-Stressed Fastener Holes for Enhanced High Cycle Fatigue Life: *Ravindra Kulkarni*[1]; [1]Rashtreeya Vidyalaya College of Engineering

Stress concentration features are undesirable yet unavoidable geometric features in many critical components of automobiles and aero engines. They increase the operating stresses resulting in non-linear material behaviour and reduction in fatigue life. In the aerospace industry the fastener hole is considered as potential crack initiation site for components under fatigue. Pre-stressing is used to introduce compressive residual stress field surrounding the hole which enhances the service life of components. Split-Sleeve method was employed for pre-stressing. The investigation aims at optimizing the working as well as design parameters involved in pre-stressing on different materials subjected to HCF. The results were fed into the MATLAB software and various surface plots were generated. Also, the equations governing the behaviour of each material were obtained by multiple linear regression analysis. The results proved substantial increase in the Fatigue life and specimens were sustained upto 10^5 stress cycles.

Microstructure-Sensitive Notch Root Analysis for Ni-Base Superalloys: *Yustianto Tjiptowidjojo*[1]; Craig Przybyla[1]; Mahesh Shenoy[1]; David McDowell[1]; [1]Georgia Institute of Technology

Macroscopic viscoplastic constitutive models for Ni-base superalloys typically do not contain an explicit dependence on the underlying microstructure. Microstructure-sensitive models are of interest since the distributions and morphology of the precipitate phase can substantially affect the stress-strain response. The primary microstructure attributes that can significantly affect the stress-strain response of IN100 are the grain size distribution and tertiary, secondary and primary γ' precipitate volume fractions and size distributions. An Artificial Neural Network (ANN) is used to inform the dependence of material parameters in an internal state variable cyclic viscoplasticity model on these microstructure attributes for microstructures within the range in which the ANN was trained using a combination of experiments for actual microstructures and polycrystal plasticity calculations performed on a large number of virtual microstructures that are intermediate to actual microstructures. The polycrystal plasticity model was calibrated to experimentally measured responses of known microstructures. Such a model is applied to examples of notch root analyses to explore the potential impact of microstructure-sensitive constitutive models in fatigue design of structures.

Effect of Carburizing Variables on the Fatigue Behavior of Carburized C015 Low Carbon Steel: *Jamal Sultan*[1]; [1]Mosul Technical Institute

Low carbon steel specimens type C015 were case carburized by using different carburizing temperatures 850-1050°C for (2-8) hours.The carburized specimens were then heat treated by using different austenizing and tempering temperatures. The effect of carburizing time, carburizing temperature and the heat treatments on the fatigue behavior have been studied and compared with noncarburized specimens of the same material. Experimental results showed that, increasing both carburizing temperature and time have a significant effect on the fatigue life of the steel specimens where as austnizing and tempering temperatures in the heat-treatment have a large effect on the fatigue life of the carburized steel. For all tests the results reveled that the carburized steel specimens have a very high cycle fatigue life and a lower crak growth rate as compared with those of non carburized steel specimens.

Effect of Alumite Treatment on Ultra-Long-Life Fatigue Property for Aluminum Alloy in Rotating Bending: Tatsuo Sakai[1]; *Yuki Nakamura*[1]; Hideo Hirano[2]; [1]Ritsumeikan University; [2]Matsushita Electric Industrial Company, Ltd.

Various kinds of aluminum alloys have been used as structural materials from a viewpoint of the lightweight. Easiness of recycle is another reason why they are widely used as mechanical components in various fields of the present industries. Long term use of the mechanical structures provides us a saving of the resources and the reduction of the environmental load in the process of steel making. Accordingly, the long term service of the mechanical products can give a key technology to keep the sustainable development of our society. However, fatigue characteristics in the long life regime for such aluminum alloys remain unsolved in comparison with ferrous metals. Thus the fatigue properties in the high cycle regime for an aluminum alloy with some different alumite treatments were experimentally examined by using a multi-spindle rotating bending fatigue-testing machine. Experimental results were discussed paying a particular attention to the effect of the surface treatments.

The Effect of Thread Dimensional Non-Conformances on the Fatigue Performance of Threaded Fasteners: *Brian Munn*[1]; [1]Oakland University

This paper presents an experimental investigation of the effect of thread dimensional non-conformance on the fatigue performance of threaded fasteners. Test specimens are dimensionally inspected according to the DIN 933 (ISO 4017) specifications for the conformance of pitch diameter and thread root radius. Additionally, the effect of the head-to-shank fillet radius is investigated. All dimensional inspections are carried out using optical methods. Axial load fatigue tests are performed in accordance with ISO 3800:1933(E). A bolt preload equal to 75% of its proof load is used. The minimum-to-maximum stress ratio used in all fatigue tests is 0.9. Fracture surfaces of the tested bolts are examined under a Scanning Electron Microscope (SEM). Data from the fatigue tests is analyzed for the effect of dimensional non-conformances on the fatigue performance.

The following abstract was moved to page 21 in the Influence of Environment and Temperature session at 3:20 PM

Effects of Surface Finishing and Tempering Temperature on Very High Cycle Fatigue Property in High Strength Steels: *Takashi Matsumura*[1]; Yasuo Ochi[1]; Kiyotaka Masaki[1]; [1]University of Electro-Communications

In order to investigate effects of surface finishing and tempering temperature on the fatigue properties of high strength steels in very high cycle regime to over 10^9 cycles, cantilever type rotating bending fatigue tests were carried out for nickel-chrome-molybdenum (JIS SNCM 439) high strength steels which were finished by the electro-polishing on the steel surface and/or tempered at four kinds of temperature of 160°C, 300°C, 500°C and 620°C. The fracture surface observed with a field emission type scanning electron microscope (FE-SEM) after the fatigue tests in order to specify the fracture origin sites. As results of fatigue tests, the electro-polishing steels showed the same typical duplex S-N curve characteristics as grinding steels. The steels tempered at 160°C showed the typical duplex S-N curve characteristics. The steels tempered at 300°C, 500°C and 620°C almost showed surface fracture type.

Effects of Carburizing Temperature on Near-Surface Characteristics that Influence Rolling Contact Fatigue Performance: *Mikolaj Bykowski*[1]; George Krauss[1]; John Speer[1]; [1]Colorado School of Mines

The effects of increased gas carburizing temperature on metallurgical factors that influence rolling contact fatigue (RCF) performance in gear steels are explored. Two steels, 4120 and 4320, were selected based on their varying propensity for oxidation, which could be an important factor influenced by carburizing temperature. RCF specimens, machined from 4120 and 4320 stock by wire EDM, were gas carburized at temperatures of 899°C (1650°F), 954°C (1750°F), and 1010°C (1850°F) to a target case depth of 0.9 mm. The surface carbon content varied between 0.84 and 1.0 wt% resulting in a variation in retained austenite content. Microstructure, prior austenite grain size (PAGS), extent of intergranular oxidation, and non-martensitic transformation products were characterized by light optical (LOM) and scanning electron (SEM) microscopy. All microstructures were fully martensitic with a plate martensite morphology in the case and lath martensite morphology in the core. Core PAGS was fine in the 899°C condition, mixed in the 954°C condition, and mostly coarse in the 1010°C condition. There was little variation in the case grain size. Significant intergranular oxidation was observed in both steels, but to a greater extent in the 4120 grade. The depth of oxidation was observed to decrease with increasing carburizing temperature, while the thickness of the oxides increased. Globular oxides near the surface dominated steel carburized at the lowest temperature while elongated oxides resulted from the highest carburizing temperature. No non-martensitic transformation products were detected. Initial rolling contact fatigue testing with a ball-on-rod RCF tester at 5.4 GPa showed that some specimens carburized at 1010°C began to fail at significantly lower number of cycles (~10 million) compared to the first failures at much higher cycles (~30 million) in specimens carburized at 899°C and 954°C.

Ultrasonic Fatigue of Surface-Treated 316 Stainless Steel: Christopher Szczepanski[1]; *J. Jones*[1]; Christopher Torbet[1]; Arthur Heuer[2]; [1]University of Michigan; [2]Case Western Reserve University

The fatigue behavior of 316 Stainless Steel has been examined in the lifetime range of 106 to 109 using ultrasonic fatigue. Tests were conducted at ambient temperature under axial, fully reversed loading (R=-1) at a frequency of 20kHz. The role of surface modification by carburization on fatigue life and fatigue crack initiation behavior in the very high cycle fatigue regime has been determine and compared with the behavior observed at conventional frequencies. For both cases a transition from surface crack initiation to subsurface crack initiation is observed with surface modification. The microstructural features responsible for crack initiation are described and the role of surface modification on fatigue life is discussed.

CANCELLED

High Cycle Fatigue Fracture of Cantilevered Specimens with Several Notches: *Ludmila Botvina*[1]; [1]Baikov Institute of Metallurgy and Material Sciences, Russian Academy of Sciences

The developed methodology of the study of the structural features of fatigue fracture is based on using specimens with five notches. The specimens were tested in conditions of cantilever rotational bending; therefore stress amplitudes in specimen section were different. This permitted the observation of the initiation and propagation of short fatigue cracks in the tips of four notches after the failure of the specimen over the fifth section at the maximum stress amplitude. The longitudinal metallographic sections of tested samples were examined. Using this method, specimens from two steels and titanium alloy were tested. The fatigue curves of crack initiation and propagation were plotted. The lengths, openings and propagation rates of small fatigue cracks were estimated, and the structural features of fatigue fracture determining the crack trajectories at various stress amplitudes and the fracture mechanism in long-life region were studied. Based on the experiment, an accelerated method of fatigue strength evaluation in the high cycle regime was proposed.

Photo Elastic Stress Measurement on Pre-Stressed Fastener Holes for Improved High-Cycle Fatigue Performance: *Srinivasa Sharma*[1]; N. Shanmukha[1]; [1]Rashtreeya Vidyalaya College of Engineering

With the need for higher strength to weight ratio of engineering components, fatigue has become an important consideration in automobiles and aircrafts components design, The highest incidence of aircraft structural fatigue has been associated with holes in fastener joints. Pre-stressing is often used to introduce beneficial compressive stresses around fastener holes to retard or arrest cracks in fatigue-loaded components.This paper highlights the effect of pre-stressing on the high cycle fatigue life of 7050-Alumininm specimens. Pre-stressing of a hole involves plastically deforming the material in both radial and hoop directions. Split-Sleeve method was adopted and specimens of varying extent of expansions were tested for HCF in a fatigue Machine. Analysis revealed fatigue life improvement and specimens were sustained up to 10^5 stress cycles. The optimum expansion of the hole for maximizing fatigue life and stresses associated with that expansion were also determined and compared with Photo elastic stress analysis.

3D Modeling of Potency for Fatigue Crack Nucleation at Primary Inclusions in Carburized and Shot Peened Gear Steels: *Rajesh Prasannavenkatesan*[1]; Jixi Zhang[1]; David McDowell[1]; [1]Georgia Institute of Technology

The objective of this work is to develop a means to study fatigue crack nucleation at subsurface in carburized and shot peened gear steels. An algorithm is presented to simulate the residual stress distribution induced through carburization and shot peening and a methodology to analyze potency of fatigue crack formation at inclusions in components subjected to cyclic bending. Rate-independent 3D finite element analyses were performed to evaluate cyclic plastic deformation in processing and service. The matrix was modeled as elastoplastic material with kinematic hardening. Idealized elastic inclusions were considered to study the potential for fatigue crack nucleation at various case depths within the specimen, considering intact and cracked inclusions as well as intact and debonded interfaces. The nonlocal average value of maximum plastic shear strain amplitude was used in a modified form of the Fatemi-Socie parameter in the proximity of inclusions as an indicator of potency to nucleate fatigue cracks.

Initiation Mechanisms, Surface vs. Subsurface Initiation

Investigation of Microstructural Changes within White Etching Area (“Butterfly”) under Rolling Contact Fatigue (RCF) Using TEM and 3D Crack Reconstruction by Focused Ion Beam (FIB): *Aleksandro Grabulov*[1]; Ulrike Ziese[2]; Henny W. Zandbergen[2]; [1]Delft University of Technology, Netherlands Institute for Metals Research (NIMR); [2]Delft University of Technology

Rolling contact fatigue (RCF) is an extreme high-cycle fatigue process (10^9 load cycles or more), involving very small-scale plastic deformation in the steel matrix adjacent to stress-raising nonmetallic inclusions, leading to the formation of so-called butterfly cracks. This paper presents TEM and Dual Beam (combination of SEM and Focused Ion Beam-FIB), investigations performed on the White Etching Area (WEA) (the “butterfly wings”) surrounding the butterfly cracks. The material investigated is a hardened and tempered model steel with a matrix composition similar to the commercial steel grade, SAE 52100 that is widely used for bearing applications, containing artificially introduced spherical Al_2O_3 inclusions. The TEM samples, containing the cracks, were selected from specific locations using precise FIB preparation process, allowing the TEM analyses of the large microstructural changes in the butterfly wing between the butterfly crack and the steel matrix around it. The results show a formation of the nano-crystalline ferrite that is not uniformly distributed inside the butterfly wing, while the steel matrix is still unchanged (tempered martensitic structure). This paper presents a 3D reconstruction of the butterfly cracks caused by RCF. Series of cross sections were produced along the crack by Dual Beam, using the Ion beam “Slice and View” method. It allowed a complete 3D crack reconstruction.

A Study on Ultra-Long Life Fatigue Characteristics of Maraging Steels with/without Aging Treatment in Rotating Bending: Tatsuo Sakai[1]; *Akiyoshi Nakagawa*[2]; Ayako Uchiyama[1]; Toshiki Ohnaka[3]; [1]Ritsumeikan University; [2]Hitachi Plant Technologies, Ltd.; [3]Nippon Koshuha Steel Company, Ltd.

Maraging steel is one of typical high strength steels used for light-weight mechanical structures due to the significant high strength higher than 2000MPa. This steel is melted in vacuum furnace in order to reduce the contents of unexpected inclusions. Thus, high quality of the mechanical properties was achieved. After solution treatment was performed, an appropriate aging treatment was applied to this steel to provide the designed strength level. From this point of view, a number of specimens in the hourglass type were prepared and half of them were solution-treated, and remaining half were aged after solution treatment. Thus, ultra-long life fatigue properties for both kinds of specimens were examined in rotating bending, and very high cycle fatigue behaviors of both steels were compared with each other.

Evaluation of the Giga-Cycle Fatigue Strength, Crack Initiation and Growth in High Strength H13 Tool Steels: *Vitaliy Kazymyrovych*[1]; Jens Ekengren[2]; Jens Bergström[1]; Christer Burman[1]; [1]Karlstad University; [2]Karlstad University

The development and use of high performance steels, like tool steels, in advanced applications require reliable very high cycle fatigue (VHCF) properties. However, supporting knowledge and data are not available. This paper concerns VHCF properties of high strength tool steels obtained during staircase testing using an ultrasound high frequency (20 kHz) test equipment. The evaluation of the fatigue mechanisms operating in the ultra high cycle regime during crack initiation and growth is made by means of high resolution FEG-SEM. The experimental results with consideration of the local stress in the fatigue initiation zone, obtained through FEM analysis, are compared to the theoretical calculations made using a fatigue crack evaluation model. Furthermore, the correlation is made between the VHCF performance of steel batches and their various inclusion contents. Comparison of VHCF results (10^9 load cycles) with HCF (10^6 load cycles) in conventional testing for an H13 steel is presented.

Ductile-Brittle Fracture Transion in Ultrasonic Fatigue of Nickel-Base Superalloy: *Qiang Chen*[1]; Norio Kawagoishi[2]; Qingyuan Wang[3]; Gen Hashiguchi[4]; Hideo Horibe[1]; [1]Kochi National College of Technology; [2]Kagoshima University; [3]Sichuan University; [4]Kagawa University

Fracture behavior in the domain of 10^9 cycles was investigated with nickel-base superalloy under ultrasonic fatigue in ambient air at room temperature. The influence of ultrasonic frequency on fracuture mechanism in the alloy was examined by comparing fracture morphologies under ultrasonic fatigue with those in conventional fatigue. Transition of fracture mode from transgranular ductile fracture to cleavage-dominated fracture occurs beyond a critical stress intensity factor range of approximately 21 MPa√m, leading to catastrophic failure under ultrasonic fatigue.

CANCELLED
A Study of Fatigue Crack Growth 5052 Aluminium-Alloy under Constant-Amplitude Loading: *Raghuvir Kumar*[1]; Mayank Gangwar[1]; [1]Motilal Nehru National Institute of Technology

Crack propagation experiments were performed on 5052 aluminum alloy for various load ranges and stress ratios. At constant maximum load, the life of the specimen increased as the load ratio increased. The crack growth data were analysed in terms of ΔK_f as a function of stress ratio R. The data covered R values of 0.0, 0.2, 0.3, 0.4 and 0.5, and a good relation was obtained for $U=0.50+0.35R+0.15R^2$. A crack growth rate equation was also developed i. e. $da/dN=5.4096X10^{-11}\ (U\Delta K)^{5.0236}$.

Microstructure

Fatigue Behavior of C38M Steel up to Very High Cycles: *Tang Li*[1]; Y. Liu[1]; M. Sriraman[1]; Q. Wang[1]; [1]Sichuan University

With the absence of an "endurance limit" in the vicinity of a million cycles, even in ferrous alloys, materials do not enjoy infinite life. Instead there is a strong likelihood of their failure in the very high cycle regime. On the other hand, there has also been an emphasis on trying to extend the service lives of various applications particularly in the automotive and power generation systems, to gigacycles, for economic and environmental considerations. Thus, the understanding of their very high cycle fatigue characteristics becomes extremely important. The present paper deals with experimental studies on the long life fatigue behavior of C38M, a ferritic-pearlitic low alloy medium carbon steel used as crankshaft material in automotive applications. Specimens of hourglass shape were fatigue tested in air at room temperature under fully reversed push-pull loading conditions (R=-1). Ultrasonic fatigue testing using a piezoelectric fatigue machine operating at 20 kHz frequency was employed to generate such high cycles within a realistic timeframe. The S-N data was obtained and the fractures analyzed by scanning electron microscopy. Preliminary results indicate that failure up to the gigacycle regime triggered by subsurface crack initiations from inclusion sites occurs in this steel as well.

CANCELLED
Fatigue Behavior of Ti-6Al-4V Alloy in Very High Cycle Regime: Jing-hui Zuo[1]; *Zhong-guang Wang*[2]; En-hou Han[1]; [1]Environmental Corrosion Center, Institute of Metals Research, Chinese Academy of Sciences; [2]Shenyang National Laboratory for Materials Science, Chinese Academy of Sciences

The very high cycle fatigue behavior of Ti-6Al-4V alloy with the bimodal and basketweave microstructure has been investigated using the ultrasonic fatigue testing system. The results show that the S-N curves of Ti-6Al-4V with both microstructures continuously decrease with increasing the number of cycles to failure, thereby no fatigue limits exist in the regime of 10^5~10^9 cycles. Compared with results under conventional loading frequency of 25Hz, the lifetime of specimen tested with ultrasonic frequency is moderately prolonged. Based on the strain rate and the heating induced by internal friction, the mechanism of frequency effect on fatigue has been discussed. SEM observation of fracture surface indicates that the crack initiation sites may change from the surface to interior of specimen with the increase in the number of cycles to failure.

NOTES

Advanced Materials and MEMS

Tuesday AM Room: Rackham Amphitheatre
August 21, 2007 Location: Rackham Center

Session Chairs: Robert Ritchie, University of California; Christopher Muhlstein, Pennsylvania State University

8:30 AM Keynote
Fatigue Behavior of Ultrafine-Grain Copper in Very High Cycle Fatigue Regime: *Petr Lukas*[1]; Ludvik Kunz[1]; Milan Svoboda[1]; Otakar Bokuvka[2]; [1]Academy of Sciences; [2]University of Zilina

Fatigue strength of ultrafine-grain (UFG) copper of purity 99.9 % produced by equal-channel angular pressing (ECAP) was determined at an ultrasonic frequency and compared with the fatigue strength of conventional-grain (CG) copper cycled at the same frequency range. The fatigue strength of UFG copper is by a factor of about 2 higher than that of CG copper in the whole very high cycle fatigue (VHCF) regime. After fatigue loading, no changes of grain morphology were detected by means of transmission electron microscopy and electron back scattering diffraction. Surface fatigue slip markings were observed only in the vicinity of the fatal crack. They followed the trace of the shear plane of the last ECAP pass.

9:00 AM Keynote
Deformation and Fatigue of Face-Centered and Diamond Cubic Structural Films: *Christopher Muhlstein*[1]; Olivier Pierron[2]; Roi Meirom[1]; James Collins[1]; M. Zapata[3]; [1]Pennsylvania State University; [2]Georgia Institute of Technology; [3]NASA Kennedy Space Center

While thin films exhibit constitutive behavior reminiscent of bulk materials, the fine scale of grain morphologies, defect structures, and surface layers can significantly alter how the material responds to cyclic loading conditions. This presentation will compare and contrast the fatigue failure mechanisms observed in thin film face-centered cubic metals (e.g., Ni and Pt), and diamond cubic semiconductors (e.g., silicon) at room temperature. Structural films tested in controlled atmospheres were susceptible to fatigue, but they were not necessarily more resistant to degradation than their bulk counterparts. Scanning and transmission electron microscopy show that the performance of these thin film materials during cyclic loading is inextricably linked to contributions from surface reaction-layer and sub-surface degradation mechanisms.

9:30 AM Keynote
An Assessment of Very High Cycle Fatigue Failure in Micron-Scale Polycrystalline Silicon for MEMS: *Robert Ritchie*[1]; Daan Alsem[1]; [1]University of California

Fatigue failure in micron-scale polycrystalline silicon structural films, a phenomenon that is not observed in bulk silicon, can severely impact the durability and reliability of microelectromechanical system (MEMS) devices. Despite several studies on the fatigue behavior of these films, there is still an on-going debate on the precise mechanisms involved. We examine here the effects of cyclic and maximum stress, loading frequency and environment in order to provide some mechanistic basis for this surprising phenomenon. Results on a broad range of testing systems from a large number of separate investigations are interpreted in terms of a "reaction layer" fatigue mechanism, where moisture-assisted subcritical cracking within the thickened oxide layer is reasoned to occur until the crack reaches a critical size to cause catastrophic failure of the entire thin film device.

10:00 AM Invited
Fatigue at Ultra High Frequencies in Sub-Micron Thin Metal Films: Oliver Kraft[1]; *Christoph Eberl*[1]; A. Walcker[1]; [1]Institut für Zuverlässigkeit von Bauteilen und Systemen, Universität Karlsruhe (TH)

Typical operating frequencies in modern communication devices reach the GHz regime, and as a result, fatigue effects are crucial in terms of reliability of micromechanical components in such devices. This paper concentrates on fatigue mechanisms in thin metal films under these conditions. Here, the dimensional constraint and the high frequencies lead to significant differences in fatigue behavior compared to bulk material. For instance, it has been shown that long range dislocation structures cannot be formed in films with sub-micron film thickness and grain size. Specifically, experimental results for Al films on piezoelectric substrates, stressed at about 1 GHz, will be presented. By combined focused ion beam and scanning electron microcopy, the resulting damage structure has been observed as voids and extrusions. This indicates that point defects and diffusional processes play an important role. However, by the use of discrete dislocation dynamics we demonstrate that dislocation based mechanisms are still active at frequencies in the GHz regime. Further, it is argued that dislocation annihilation mechanisms trigger atom transport, which leads to the observed void and extrusion formation. Based on the experimental observations and the dislocation modeling, a strategy for the lifetime prediction of metal thin films will be discussed.

10:20 AM
Very High Cycle Fatigue Characterization of Silicon Structural Thin Films with kHz Frequency Resonators: *Olivier Pierron*[1]; Christopher Muhlstein[2]; [1]Qualcomm MEMS Technologies; [2]Pennsylvania State University

The development of test vehicles dedicated to address long-term reliability issues specific to microelectromechanical system (MEMS) devices is a necessary activity for a growing MEMS industry. On-chip kHz resonators have been successfully employed to determine the fatigue behavior of micron-scale Si films and to investigate the underlying mechanism(s). In addition to stress–life fatigue curves up to 100 billion cycles, these fatigue characterization structures have the unique ability to track how accumulated damage changes the compliance of the test specimen. However, this critical insight into the degradation mechanism is contingent upon proper control of experimental parameters (temperature, humidity, vacuum level). This talk will present the testing methodology that was followed to assess the critical role of the environment on the fatigue damage accumulation of mono- and poly-crystalline silicon films. The implications of the experimental results will be discussed in light of the current proposed mechanisms.

10:40 AM Networking Break and Poster Viewing

11:10 AM Invited
Mechanical Fatigue of Polysilicon: *Arthur Heuer*[1]; Hal Kahn[1]; R. Ballarini[1]; L. Chen[1]; Frank Ernst[1]; Gary Michal[1]; [1]Case Western Reserve University

Polycrystalline silicon (polysilicon) fatigue specimens with micrometer-sized dimensions were fabricated and subjected to cyclic loading using an integrated electrostatic actuator. The actuator was capable of applying positive and negative mean stresses in addition to cyclic stresses, so that the load ratio R was varied from -3 to 0.5. Several seemingly contradictory aspects of polysilicon fatigue behavior were observed: At shorter lifetimes (<50,000 cycles) there was no difference between testing in air or vacuum, while at longer lifetimes (>50,000 cycles) there was a significant effect of the testing ambient. For large stress amplitudes (maximum stress minus minimum stress in the cycle), increasing the mean stress weakened the material, while for low stress amplitudes, increasing the mean stress strengthened the material. Strengthening was observed for both tensile and compressive stress cycles. Preliminary microscopy investigations did not reveal any microstructural changes (surface oxide growth, phase transformations, etc.) due to cycling. Therefore, we postulate mechanical mechanisms for the observed phenomena.

11:30 AM
High Cycle Fatigue Crack Behavior and Fracture in Poly Si Thin Films: *Qiang Chen*[1]; Gen Hashiguchi[2]; Norio Kawagoishi[3]; Katsuyori Suzuki[2]; Yuki Nishimori[2]; Hideo Horibe[1]; [1]Kochi National College of Technology; [2]Kagawa University; [3]Kagoshima University

High cycle fatigue strength and fracture mechanism of poly Si thin films were investigated using a novel strain controlled, free standing tensile fatigue device within a scanning electron microscope (SEM). The initiation and propagation of small cracks were examined. The combination of transmission electron microscope (TEM) and focused ion beam (FIB) technologies was employed to investigate the fracture mechanism. The scale effects involved was discussed.

11:50 AM
Fatigue of Polycrystalline Thin Film Silicon for Micro-Electro-Mechanical Structures (MEMS): *Joerg Bagdahn*[1]; Matthias Ebert[1]; Peter Gumbsch[1]; Robert Boroch[2]; [1]Fraunhofer-Institute for Mechanics of Materials; [2]Roland Müller-Fiedler

Polycrystalline silicon is the dominating material for MEMS devices, like acceleration sensors or gyroscopes for automotive applications. The detection systems of MEMS, e.g. gyroscopes, require the permanent vibrating at the eigenfrequency, which exceeds normally 10kHz. Thus, these device can undergo extremely high number of cycles (>1011) during the service time of 15 years. In this paper a new fatigue test sample for testing at ~90 kHz will presented. This sample allows to apply 10^{11} cycles in 1½ months. A statistical significant amount of tests at different load levels could be performed since the test setup is designed for a parallel testing of up to 25 samples. It was found in this investigation that the material shows a strengthening effect during loading with small amplitudes and fatigues at high loads. Microstructural investigations (SEM,TEM, FIB, AFM, EBSD) and numerical simulation techniques were applied to explain this behaviour.

12:10 PM Invited
High-Cycle Fatigue Behavior of Zr-Based Bulk Metallic Glasses: Gongyao Wang[1]; *Peter Liaw*[1]; Y. Yokoyama[2]; A. Peker[3]; B. Yang[1]; M. Freels[1]; R. A. Buchanan[1]; C. T. Liu[1]; A. Inoue[2]; C. R. Brooks[1]; [1]University of Tennessee; [2]Tohoku University; [3]LiquidMetal Technologies, Inc.

High-cycle fatigue (HCF) experiments were conducted on zirconium (Zr)-based bulk-metallic glasses (BMGs). The test environments were in air at room temperature. The fatigue-endurance limit of $Zr_{50}Cu_{30}Al_{10}Ni_{10}$ (865 MPa) is somewhat greater than those of $Zr_{50}Cu_{40}Al_{10}$ (752 MPa) and $Zr_{41.2}Ti_{13.8}Ni_{10}Cu_{12.5}Be_{22.5}$ (Batch 59: 703 MPa and Batch 94: 615 MPa). The fracture morphology indicates that fatigue cracks initiate from shear bands or some defects. The fatigue-striation spacing was measured in the crack-propagation region of the fatigue-fractured surface. Its relationship with the stress-intensity-factor range was developed, which is different from the empirical relationship for crystalline alloys.

Influence of Notches and Surface Conditions

Tuesday PM
August 21, 2007

Room: Rackham Amphitheatre
Location: Rackham Center

Session Chairs: Stefanie Stanzl-Tschegg, Universität für Bodenkultur Wien; Yasuo Ochi, University of Electro-Communications, Tokyo

2:00 PM Invited
Effects of Shot Peening Treatment on Very High Cycle Fatigue Property in Austempered Ductile Iron: *Yasuo Ochi*[1]; Kiyotaka Masaki[1]; Takashi Matsumura[1]; [1]University of Electro-Communications, Tokyo

Rotating bending fatigue tests were carried out on austempered ductile cast iron(ADI) with shot peening(SP) treatment, and effects of the SP treatment on fatigue properties and fracture morphologies were investigated in the very long life regime. As results, the improvement of fatigue strength for the shot peened ADI was identified before the regime of 10^7 cycles. Moreover, the S-N diagrams of the shot peened ADI and the fatigue limit of non-peened ADI crossed at 10^8 cycles. Then, the fatigue strength at 10^9 cycles of the non-peened ADI was about 360MPa and that of the shot peened ADI was about 280MPa. To investigate the reason for the fatigue strength reduction of the shot peened ADi, the residual stress distribution and the hardness distribution were measured and the fracture origins were observed by SEM.

2:20 PM Invited
Very High Cycle Fatigue Strength of Bearing Steel with Notch: *Yoshiaki Akiniwa*[1]; Keisuke Tanaka[1]; [1]Nagoya University

Ultrasonic fatigue tests and rotating-bending fatigue tests were carried out with smooth and notched specimens of a bearing steel (JIS SUJ2). For notched specimens, a circumferential notch is introduced. The effect of a notch on the S-N curve was examined. The S-N curve for all specimens obtained from ultrasonic fatigue tests was very close to that obtained from rotating bending fatigue tests. The fracture surface was examined with scanning electron microscopy to identify a crack nucleation site. The smooth specimens were broken from specimen surface and internal inclusions irrespective of fatigue life. On the other hand, most notched specimens were broken from surface. The fatigue strength of notched specimens was compared with predicted values by using point stress model, critical distance model and R-curve method. The predicted fatigue strength agreed well with experimental results.

2:40 PM
Influence of Macroscopic and Microscopic Notch Effects on the VHCF-Behavior of a Precipitation-Hardened Aluminium Alloy: *Martina Zimmermann*[1]; Hans-Juergen Christ[1]; [1]University of Siegen

Fatigue life is known to be strongly affected by notch effects, mainly resulting from geometric discontinuities, but also as a consequence of surface roughness or microstructural discontinuities. The notch-sensitivity increases with increasing life. However, the relevant nature of the notch effect is widely unknown. A typical damage mechanism in the VHCF-range is crack initiation at or close to non-metallic inclusions serving as internal stress raisers and shifting the crack initiation site from the surface to the subsurface. Hence, an evaluation of the predominance of the different notch effects strongly contributes to a better understanding of the damage mechanisms in the VHCF-range. The material analysed in this study is the precipitation-hardening Al-alloy EN-AW 6082. Cylindrical specimens of different geometrical notches, different surface qualities (as-machined, mechanically polished and electro-chemically polished) and different microstructural conditions (naturally-aged, peak-aged and overaged) were tested by means of an ultrasonic and a servo-hydraulic testing machine.

3:00 PM
Effects of Notch and Dynamic Strain Aging on Very High Cycle Fatigue Properties of Austenitic Stainless Steel at an Elevated Temperature: *Kenji Kanazawa*[1]; [1]Chuo University

Rotating bending fatigue tests were carried out for notched specimens of 316 austenitic stainless steel at 300°C. Nevertheless any nonpropagating crack was not recognized for specimens endured at 100,000,000 cycles, fatigue strength at 100,000,000 cycles did not decrease continuously with increasing stress concentration factor. An area at the root of notch hardened during fatigue test at 300°C by dynamic strain aging. The hardening behavior became remarkably with increasing stress concentration factor. Effects of stress concentration factor and hardening behavior on fatigue strength canceled each other, and then the dependency of fatigue strength on the stress concentration factor became insensitive. Fatigue strength obtained by the stress increment tests became higher than the conventional fatigue strength. The fatigue strength was very sensitive to the stress concentration factor. Histograms of hardness at the root of notch for specimens fatigued by stress increment test were similar to each other independent of stress concentration factor.

3:20 PM

Surface Effect on the Fatigue Behavior of Mechanical Components in Giga Cycle Regime: *Emin Bayraktar*[1]; Rubén Mora[2]; Israel Garcia[3]; Claude Bathias[2]; [1]Supmeca-Paris; [2]Bathias Fatigue Research Laboratory, CNAM; [3]CIICAp-UAEM

Engineering components work under different cyclic loading conditions and fatigue failure can occur after a very long life fatigue regime beyond 10^9 cycles. This work reviews the effect of surface conditions on the fatigue behaviour of mechanical components in Gigacycle regime. Evidently, surface conditions can be variable and due to the very different sources such as manufacturing effect like machining or final surface processes on the parts such as heat treatment during the manufacturing them. In fact, this is a detail comparative study based on the experimental results carried out by different research teams who work in this domain. Experimental investigation is based on the test specimens failed at a frequency of 20 kHz with different stress ratios (R=0.1 R=-1) at room temperature. All of the fatigue tests were carried out up to 10^{10} cycles. Damage mechanism was evaluated by Scanning Electron Microscopy (SEM).

3:40 PM

Very High Cycle Fatigue of Notched High Strength Steels: *Hitoshi Ishii*[1]; Hiroyasu Araki[1]; Yasuki Kudo[1]; Tooru Yagasaki[2]; [1]Shizuoka University; [2]Honda Research and Development Company, Ltd

It is known that no endurance (or fatigue) limit exists in high strength steels and their S-N curves up to the giga-cycle regime show so-called two step-wise shapes. This is true in the case of smooth specimens. However, it is found that when tested the notched high strength steel specimen common S-N curve with an endurance limit is obtained. To see the effect of notch radius on the fatigue behavior of the steels, several notched high strength steel specimens with different stress concentration factors were fatigued up to the giga cycle regime by using ultrasonic fatigue testing method. It becomes clear that nucleation of the internal fatigue fracture which cause the two step-wise shape of the S-N diagram does not occur and an endurance limit appears as the stress concentration factor increases more than 2.0.

4:00 PM Networking Break and Poster Viewing

4:30 PM

Impact of Modes of Vibration on Goodman Diagrams: A Case Study on Compressor Blades: *Ganapathi Krishnan*[1]; Robert Tryon[1]; Richard Holmes[1]; [1]VEXTEC Corporation

Aerospace companies use Goodman diagram as a basis for HCF avoidance, this method is empirically based and uses the material ultimate or yield strength and fatigue endurance limits to set-up the allowable and steady state stress limits. Resulting Goodman curve is applied to all vibratory modes and all blade geometries in a ‘one size fits all’ approach. The VEXTEC modeling approach uses the probabilistic microstructural fatigue life prediction tool VPS-MICROTM developed in-house along with finite element analysis to develop a ‘simulated Goodman’ for each blade geometry and each mode of vibration. The premise being that the magnitudes of stress and stressed volume drive the fatigue response of a blade in a certain mode and that different modes have different volumes of material stressed. This approach has been applied to a tenth stage compressor blade of a land-based turbine for mode 1 and mode 2 and has been validated through experiments.

4:50 PM

Very High Cycle Fatigue Behaviour of Two Different Aluminium Wrought Alloys: *Brita Pyttel*[1]; Daniela Schwerdt[1]; Christina Berger[1]; [1]Technische Universität Darmstadt

Investigations at room temperature were carried out with smooth and notched specimens made of the aluminium alloy EN AW 6082, smooth specimens made of EN AW 6056 in two different materials states, notched specimens made of EN AW 6056 and screws M8 made of EN AW 6056 with series with thread rolling before and after heat treatment. Fatigue tests were done with a servohydraulic testing machine and a resonant frequency machine. Tests run up to a maximum number of cycles of N = 10^9 or $2•10^8$. Crack initiation sites could be found below the surface for smooth aluminium specimens of EN AW 6082 but not for screws and other notched specimens. Fracture surface and microstructure of the crack initiation sites were observed by means of SEM, EDX and metallographic methods. The investigations are a part of a german research program involving 5 research institutes.

5:10 PM

Gigacycle Fatigue Behavior of Cold Forging Die Steels: Hideki Kobayashi[1]; *Ryuichiro Ebara*[2]; Atsushi Ogura[3]; Yasuyuki Kondo[3]; Shinichi Hamaya[3]; [1]Kagawa University; [2]Hiroshima Institute of Technology; [3]Nichidai Corporation

Fatigue strength of SKH51 steel at 10^9 cycles was 790MPa and 83MPa higher than that of 0.65 mass% carbon matrix high speed steel. For both steels the lapped specimen with surface roughness, R_z of 0.17±0.7μm increased fatigue strength of the as-machined specimen with surface roughness, R_z of 5.1±0.7μm. Gigacycle fatigue strength of both steels heat-treated in vacuum were higher than those heat-treated in salt bath. Fatigue crack initiated from internal inclusion and propagated with transgranular mode for both steels. Fatigue crack initiation behavior in giga cycle regime is discussed for high strength cold forging die steels with respect to the effect of surface roughness and heat treatment.

5:30 PM

The Nature of Multi-Modal Distribution of Fatigue Durability for Titanium Alloy VT9: *Andrey Shanyavskiy*[1]; T. Zaharova[2]; A. Potapenko[1]; [1]State Center of Civil Aviation Flight Safety; [2]State Institute of Aviation Motors, Moscow

Fatigue tests of titanium alloy VT9 were conducted under rotating bending of smooth specimens in diameter of 8mm and notched specimens with notch-radius of 0.25mm at environmental temperature 200°C, 300°C and 500°C. Statistical analysis has shown bimodal distribution of fatigue durability for tested specimens in area of $N_f \leq 5.108$ cycles. Two branches of the S-N curve were detected with bifurcation area which was in the range of stress amplitudes 400–550MPa for smooth specimens tested at 500°C. The fractographic analysis used to reveal distinction in mechanisms of fatigue cracks origination for the left and right branches of the S-N curve. In all tested specimens cracks development begins at the surface. The mechanical stress concentration at the scratch tip dominates and determines the macro scale level of the fatigue crack origination that reflected left branch of the S-N curve. The right hand of the S-N curve takes place because of the crack initiation in the brittle surface lyre, being physical stress concentrator on the meso-scale level. Nevertheless, despite of scratches and brittle lyre, in area of durability more than 5.10^8 cycles cracks origination occurred under the specimen surface and the third branch of the S-N curve have to be seen on the micro-scale level for fatigued material. The paper includes a discussion of these three possibilities to originate fatigue cracks based on the discovered brittle fracture of the investigated material under the surface for monotonically tensed specimens, which were preliminary fatigued without fracture up to 5.10^8 cycles.

Recent Advances in Apparatus and Instrumentation

Wednesday AM Room: Rackham Amphitheatre
August 22, 2007 Location: Rackham Center

Session Chairs: Martina Zimmermann, University of Siegen; James Larsen, US Air Force

8:30 AM Keynote
Fatigue Damage of Low Amplitude Cycles under Variable Amplitude Loading Condition: *Herwig Mayer*[1]; [1]Universität für Bodenkultur Wien

Ultrasonic fatigue tests are performed with 0.15% C steel, which shows an endurance limit in S-N tests. Two-step variable amplitude loading experiments serve to investigate the influence of numerous cycles below the endurance limit on fatigue damage. If high stress amplitudes of the loading sequences are more than approx. 15% above the endurance limit, low load cycles contribute significantly to fatigue damage. Investigations of fatigue crack propagation under two-step variable amplitude loading show accelerated crack growth caused by low load cycles. If high stress amplitudes of the two-step sequences are less than 15% above the endurance limit, beneficial influences of numerous low load cycles are found. Under these conditions for the high load, the material can sustain far greater numbers of load cycles than predicted by Miner damage accumulation calculation. Fatigue cracks can stop propagating although the high stress intensity amplitude of the variable loading sequence is above the constant amplitude threshold.

9:00 AM Invited
A 20 Kilohertz Optical Strain Gage: *William Sharpe*[1]; [1]Johns Hopkins University

Strains can be measured over very short gage lengths (100-300 microns) by optical interferometry from two reflective markers on a specimen. This technique, which has been used in numerous quasistatic and some dynamic studies at both room and high temperatures, is extended to high frequencies with photomultiplier tubes and a laboratory computer. The system is described, and measurements of cyclic strains as large as 4500 microstrain at 20 KHz are demonstrated. Crack opening displacements can also be measured, and strains at 590°C have been measured.

9:20 AM
New Measuring Methods for the Fatigue Assessment of Metals in the Very High Cycle Regime: Michael Koster[1]; *Guntram Wagner*[1]; Frank Walther[1]; Dietmar Eifler[1]; [1]University of Kaiserslautern, Institute of Materials Science and Engineering, Kaiserslautern, Germany

Essential requirements for powerful measuring methods to be used for the fatigue assessment of metals in the very high cycle fatigue (VHCF) range are a sufficient high-resolution measurement of an ultrasonic oscillation and non-contact sensor systems in order to prevent coupling and mass effects between the sensors and the specimens. For the investigations at the Institute of Materials Science and Engineering (WKK) at the University of Kaiserslautern a laser doppler vibrometer (LDV) in combination with a newly developed software package, which enables a recording speed of 5×10^5 samples per second, were used to measure the relevant data during the ultrasonic fatigue test. The purpose was to develop suitable measuring techniques to characterize the cyclic deformation behavior and microstructural changes in metals in the VHCF regime between 10^8 and 10^{10} cycles. Additionally, the generator power was measured online to indicate fatigue cracks in the specimens.

9:40 AM
Accrual of Small Fatigue Crack Damage in Ti-6Al-4V Under Resonant Mini-Sweep Loading: *Michael Caton*[1]; Ryan Morrissey[1]; [1]U.S. Air Force

In the aerospace industry, rotating engine components are subject to resonant vibratory loads under various operating conditions. These vibratory loads are typically experienced for only brief periods as the rotational speed of the engine traverses critical modes. These relatively brief bursts of resonant vibration, referred to as “mini-sweeps,” can contribute to the initiation of fatigue cracks, or the propagation of existing fatigue damage. This study investigates the propagation of small fatigue cracks in Ti-6Al-4V under mini-sweep loading conditions. Bursts of resonant, fully-reversed loading were applied to cylindrical, dog-bone specimens at a frequency of 20 kHz at room temperature using an ultrasonic transducer. The growth of small fatigue cracks, initiated from artificial notches, was monitored using a standard replication technique. The small crack propagation behavior under these loading conditions will be presented and the implications for improved lifing methods of critical rotating components will be discussed.

10:00 AM
A New High Speed (150 Hz) Rotating Bending Fatigue Test Machine: *Gonzalo Dominguez*[1]; Mauricio Guzman-Tapia[1]; [1]University of Michoacan

A new machine to perform rotating bending fatigue tests at high speed (150 Hz) is presented in this work. A general description of this machine is developed concerning its design and operation, and regarding the capacity to attaint the very high cycle fatigue regime. To carry out tests at very high number of cycles, it is necessary to estimate the magnitude and to know the localization of highest strain and stress zones associated with crack initiation and fatigue failure. Influence of the parameters: applied load, rotating speed and geometry of the specimen on rotating bending fatigue are obtained by simulation with the aid of Visual-Nastran software. Finally, tests on the AISI-SAE 1018 steel are performed using this machine, the results are shown and discussed according the evolution of fatigue life and the observed fatigue failure origin.

10:20 AM Networking Break and Poster Viewing

Life Predictions, Uncertainty and Statistical Analysis

Wednesday AM Room: Rackham Amphitheatre
August 22, 2007 Location: Rackham Center

Session Chairs: Martina Zimmermann, University of Siegen; James Larsen, US Air Force

10:50 AM Invited
Data Fusion and Science Based Modeling: A Technique for Very High Cycle Fatigue Predictions: *D. Harlow*[1]; [1]Lehigh University

Experimental programs in very high cycle fatigue demonstrate that the data contain significant uncertainty, which cannot be eliminated. It must be considered in design and life-cycle predictions, especially for high reliability applications where supporting data are scarce. A methodology is proposed that incorporates uncertainty, from all sources, into modeling and predictions. The synergy of modeling and data is demonstrated by calibration of simulations generated from a scientifically based model with the data to include the uncertainty and minimize the data required for predictions. An extensive set of data for SUJ2 steel will be used for the demonstration. SUJ2 exhibits bimodal damage growth. One mode is associated with damage nucleating from internal particles, and the other is surface induced damage. Consequently, a methodology that reasonably and accurately predicts very high cycle fatigue behavior that results from multiple modes of damage growth by infusing limited data with fatigue modeling is warranted.

11:10 AM

Statistical Approaches Applied to Very High Cycle Fatigue: *Carlos Engler*[1]; John Lasecki[1]; Robert Frisch[1]; John Allison[1]; [1]Ford Motor Company

This paper describes the use of the Maximum Likelihood Estimate to analyze the fatigue results of Staircase testing (including variable step increments and different distributions) and Life-Regression models (S-N curves). It has been observed that the fatigue strength of cast aluminum alloys continuously decreases for very high number of cycles. It has also been observed that the slope of the S-N curve is significantly lower in the very high cycle regime, and that a simple Basquin relationship cannot be used to describe the S-N curve. The Random Fatigue Limit model, however, assumes that there is a probabilistic fatigue limit at infinite life and provides a useful empirical method to describe the curvature observed in the S-N fatigue curve. It is also statistically accurate, as it uses the failures and censored data to fit the S-N curve, and constitutes the preferred method to fit the S-N curve for the alloys investigated.

11:30 AM

A Probablistic Model of Fatigue Strength Controlled by Porosity Population in Cast Aluminum: *Xiaoxia Zhu*[1]; Jianzhang Yi[1]; J. Jones[1]; John Allison[2]; [1]University of Michigan; [2]Ford Motor Company

The very high cycle fatigue behavior of E319 cast aluminum alloy was investigated using ultrasonic fatigue instrumentation operating at 20 kHz. An endurance limit was demonstrated in the lifetime regime beyond 10^7 cycles. The fatigue strength at 10^8 cycles was associated with both size and location of the initiating pores through a critical stress intensity factor for fatigue crack growth. Based on the experimental observations, a probabilistic model was developed to establish the relationship between the casting porosity population and the fatigue strength of the alloy. Good agreement was obtained between the modeling results and experiments. The effects of porosity population and specimen geometry on fatigue strength at 10^8 cycles were quantified

11:50 AM

Probabilistic Life-Prediction in the Long-Lifetime Regime: *Sushant Jha*[1]; James Larsen[2]; Andrew Rosenberger[2]; [1]Universal Technology Corporation; [2]U.S. Air Force Research Laboratory

The classical fatigue theory suggests an increasing contribution of crack initiation in the long-lifetime regime, or as the stress level is decreased. It is also known that the conventionally accepted 10^7 cycles fatigue-limit may not extrapolate to longer lifetimes. This is now widely accepted as due to a switch in the crack initiation mechanism in the long-life regime, which is often accompanied by a step in the stress vs. lifetime (S-N) behavior. In this paper we evaluate the applicability of these long-lifetime fatigue theories to probabilistic life prediction of two titanium-based materials, Ti-6Al-2Sn-4Zr-6Mo and a γ-TiAl based alloy. We show that while these theories are valid for the mean-lifetime response, they may not be sufficient to describe the fatigue variability behavior. We discuss a physics-based description of fatigue variability that suggests separate responses of the mean-lifetime (crack-initiation dominated) and the life-limiting mechanism (crack-growth), and apply it to probabilistic life-prediction.

12:10 PM

Approaches to Predict the Very High-Cycle Fatigue Behavior of Cast Aluminum Alloys: *Qigui Wang*[1]; [1]General Motors Corporation

Based on high cycle ($\leq 10^7$ cycles) behavior of aluminum castings, a probabilistic approach and a fracture mechanics method are developed. Both approaches have been validated with cast aluminum components subjected to high-cycle fatigue until 10^7 cycles. In addition to this development, an extension is proposed to improve the very long life assessment of complex structures. An extrapolation of the developed models to a very high cycle regime (10^9–10^{11} cycles) is tested and the results are also discussed.

Influence of Environment and Temperature

Wednesday PM — Room: Rackham Amphitheatre
August 22, 2007 — Location: Rackham Center

Session Chairs: Herwig Mayer, Universität für Bodenkultur Wien; Carlos Engler, Ford Motor Company

2:00 PM Conference Update

2:10 PM Keynote

Modeling Environment Sensitive Fatigue at Low Growth Rates: *Richard Gangloff*[1]; [1]University of Virginia

Environment greatly enhances fatigue cracking in the low growth rate (da/dN) regime, but mechanistic understanding at the nano to micro-scale and associated macroscopic property models are limited. For aluminum alloys in moist environments and ambient to cryogenic temperatures, fatigue damage is likely governed by the interaction of environmental hydrogen (H) with cyclic plastic strain and tensile stress highly localized about the crack tip. Models of rate limiting mass transport effectively describe the frequency-environment activity dependence of da/dN for reactive Al crack surfaces. However, such theories cannot predict absolute values of da/dN. The H-environment damage process has been elucidated by modern probes, including EBSD and TEM, but results are complex and a definitive failure criterion has not been identified to enable da/dN prediction. Governing crack tip stress and strain distributions necessary for modeling are uncertain because continuum approaches are challenged by small-length scale and microstructure effects, while dislocation models are not yet connected quantitatively to a physics-based crack advance mechanism. If advanced, these elements could model the formation and early growth of small cracks proximate to either constituent particles or corrosion topography.

2:40 PM

Effect of Frequency and Environment on High Cycle Fatigue of Cast Aluminum Alloys: *Carlos Engler*[1]; Robert Frisch[1]; John Lasecki[1]; Herwig Mayer[2]; John Allison[1]; [1]Ford Motor Company; [2]University of Agricultural Sciences

Ultrasonic fatigue testing machines working at approximately 20 kHz allow extending the number of testing cycles to the 10^8-10^{10} range. One of the questions that arise, however, is if the results from these very high frequency tests are comparable to the ones obtained from conventional tests performed at lower frequencies (up to 100 Hz). This paper compares the high cycle fatigue behavior of three cast aluminum alloys under two test frequencies (75 Hz and 20 kHz). Tests have been performed both in air and under water to demonstrate the effect of environment (i.e., the partial pressure of water vapor) on fatigue life. It has been observed that the S-N curve for some alloys is very sensitive to the testing frequency and to the environment.

3:00 PM

Effect of Frequency and Environment on Room Temperature Fatigue Performance of E319 Cast Aluminum Alloy: *Xiaoxia Zhu*[1]; Jianzhang Yi[1]; J. Jones[1]; John Allison[2]; [1]University of Michigan; [2]Ford Motor Company

The fatigue behavior of E319 cast aluminum alloy was investigated using an ultrasonic testing system operating at 20 kHz and a servo-hydraulic testing system operating at 75 Hz. In the lifetime regime < 10^7 cycles, the fatigue life at 20 kHz is approximately five to ten times longer than that at 75Hz. Fatigue tests conducted under controlled humidity in air indicate fatigue crack growth rates increase with increasing humidity level. As a result, a shorter fatigue life is registered at low loading frequency. In the lifetime regime >10^7 cycles, a fatigue limit was observed and the effect of frequency is substantially reduced. The mechanisms responsible for these observations are described.

3:20 PM
Effects of Surface Finishing and Tempering Temperature on Very High Cycle Fatigue Property in High Strength Steels: *Takashi Matsumura*[1]; Yasuo Ochi[1]; Kiyotaka Masaki[1]; [1]University of Electro-Communications

In order to investigate effects of surface finishing and tempering temperature on the fatigue properties of high strength steels in very high cycle regime to over 10^9 cycles, cantilever type rotating bending fatigue tests were carried out for nickel-chrome-molybdenum (JIS SNCM 439) high strength steels which were finished by the electro-polishing on the steel surface and/or tempered at four kinds of temperature of 160°C, 300°C, 500°C and 620°C. The fracture surface observed with a field emission type scanning electron microscope (FE-SEM) after the fatigue tests in order to specify the fracture origin sites. As results of fatigue tests, the electro-polishing steels showed the same typical duplex S-N curve characteristics as grinding steels. The steels tempered at 160°C showed the typical duplex S-N curve characteristics. The steels tempered at 300°C, 500°C and 620°C almost showed surface fracture type.

3:40 PM Networking Break and Poster Viewing

4:00 PM
A Review of Failure Mechanisms of Ultra-High Cycle Fatigue in Engineering Materials: H. Tian[1]; M. J. Kirkham[1]; L. Jiang[2]; B. Yang[1]; Gongyao Wang[1]; *Peter Liaw*[1]; [1]University of Tennessee; [2]General Electric Corporation

Fatigue behavior of engineering materials has been extensively studied. However, most published research does not extend past around 10^7 cycles. Because plots of the stress versus number of cycles to failure (S-N curves) of ferrous alloys and some other materials apparently reach a horizontal asymptote, it was assumed that specimens tested at stresses below the asymptote, called fatigue limit, would have infinite lives. However, research over the recent years has discovered fatigue failures at stresses below the fatigue limit and lives above 10^7 cycles, termed ultra-high cycle fatigue (UHCF). This paper reviews several failure mechanisms and models for UHCF, including slip mechanism, hydrogen-embrittlement mechanism, $\sqrt{area}$ parameter model, and fatigue-crack initiation at porosities and inhomogeneities.

4:20 PM
Fracture Mechanism in High Cycle Fatigue of Inconel 718 at Elevated Temperatures: *Qiang Chen*[1]; Norio Kawagoishi[2]; Masahiro Goto[3]; Qingyuan Wang[4]; Nu Yan[2]; [1]Kochi National College of Technology; [2]Kagoshima University; [3]Oita University; [4]Sichuan University

Fracture mechanism in fatigue of Inconel 718 up to 10^8 cycles was investigated at 500ºC and 600ºC. At both temperatures, fracture initiated from subsurface in the long life region beyond 10^7 cycles, though main cracks nucleated from surface in the short life region. Although surface cracking was observed even in the long life region at elevated temperatures, surface cracks stopped propagating after extending to ~20-30 μm. Instead, intergranular cracking was generated at the origins of subsurface and led to final failure.

4:40 PM
Fatigue Variability of a Single Crystal at Elevated Temperature: *Ryan Morrissey*[1]; [1]Air Force Research Laboratory

The objective of this work is to investigate the fatigue behavior of a single crystal nickel-base superalloy in the gigacycle regime. Testing from 10^6 to 10^9 cycles at 1100 F will be performed using an ultrasonic fatigue system operating at 20 kHz. Multiple tests will be performed at stresses near the fatigue limit to determine the variability in fatigue life in this regime. Comparisons with fatigue crack growth data will then be used to estimate initiation and propagation lives. Scanning electron microscopy will be used to determine the failure mechanisms and crystallographic crack paths. The results of this study will be compared to previous tests performed at conventional frequencies (20-400 Hz) as part of the National High Cycle Fatigue Program to determine the effects of frequency on the fatigue behavior.

5:00 PM
Very High-Cycle Fatigue of a Single Crystal Nickel-Based Superalloy at Elevated Temperature: *Jianzhang Yi*[1]; Tresa Pollock[1]; J. Jones[1]; Joseph Rigney[2]; P. Wright[2]; [1]University of Michigan; [2]GE Aviation

The very high-cycle fatigue behavior of a nickel-based single crystal superalloy René N5 with a platinum aluminide coating was investigated using an ultrasonic fatigue testing system, operating at a frequency of approximately 20 kHz. The single crystals were stressed along the <001> orientation with a stress ratio of 0.2 and at a temperature of 982°C up to 10^9 cycles. For the testing conditions investigated, crack initiation occurred at either the specimen surface or interior, determined by the size and spatial distribution of microstructural features in the alloy. Depending on the location of crack initiation sites and the magnitude of applied stress, crack propagation occurred either along non-crystallographic planes perpendicular to the loading axis (Mode-I crack) or along (111) octahedral planes (Mode-II crack). The role of loading frequency and microstructural features in the alloy on crack initiation and propagation behavior is discussed.

5:20 PM
Very High Cycle Fatigue Behavior of Nickel-Base Superalloy René 88DT at Elevated Temperature: *J. Miao*[1]; T.M. Pollock[1]; J. W. Jones[1]; [1]University of Michigan, Ann Arbor

The very high cycle fatigue behavior of nickel-base superalloy René 88 DT was investigated in the lifetime range of 10^5~10^9 cycles at 593°C. All the fatigue cracks initiated internally. Most of fatigue cracks nucleated in larges grains and formed large crystallographic facets. The geometrical orientation of crack facets within fatigue crack initiation sites and crystallographic crack growth regions was quantitatively studied by three dimensional reconstruction techniques. The crystallographic orientation and microstructure details of crack initiation grains were examined by using metallographic serial sectioning combined with EBSD. The fatigue crack initiation mechanisms for this alloy in the very high cycle regime will be discussed.