HIGH-CYCLE FATIGUE AND TIME-DEPENDENT FAILURE IN METALLIC ALLOYS FOR PROPULSION SYSTEMS
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Abstract

The objective of the AFOSR-MURI High-Cycle Fatigue program is to characterize and model the limiting damage states at the onset of high-cycle fatigue to facilitate mechanistic understanding as a basis for life prediction. Efforts have been focused on the influence of foreign object damage (FOD) and fretting on a Ti-6Al-4V blade alloy and a polycrystalline Ni-base disk alloy. Accomplishments from the program are outlined below:

- Worst-case fatigue threshold stress intensities have been measured in STOA (bimodal) Ti-6Al-4V using large (> 5 mm) cracks under representative HCF conditions (R > 0.95, 1000 Hz). Values provide a *practical*, frequency-independent (20 – 20,000 Hz) lower bound for the growth of naturally-initiated, physically-small (> 40 μm) cracks.
- Stress-intensity solutions have been developed for small, semi-elliptical, surface cracks under mixed-mode loading. Such solutions are being used to experimentally measure (for the first time) small-crack, mixed-mode thresholds in Ti-6Al-4V.
- Mixed-mode thresholds, at mixities of $K_{II}/K_I \sim 0.5$ to 8, for large, short and (for the first time) microstructurally-small cracks have been measured in Ti-6Al-4V, with both bimodal and lamellar microstructures. Mixed-mode short- and particularly small-crack thresholds are significantly lower than those for large cracks. Using a G-based approach, Mode I is found to be the worst-case threshold condition in the Ti-6Al-4V alloy.
- FOD, simulated with high velocity 200-300 m/s steel-shot impacts, has been found to severely reduce the smooth-bar fatigue life in Ti-6Al-4V microstructures. Whereas worst-case thresholds provide a lower-bound for high-cycle fatigue in the presence of continuum cracks, a modified Kitagawa-Takahashi is proposed where FOD-induced microstructurally-small cracks are formed in damaged regions.
- The local residual stress gradients surrounding FOD regions have been analyzed using quasi-static and dynamic numerical models; predictions have been verified using synchronous x-ray micro-diffraction techniques. X-ray studies have also focused on the cycle-dependent relaxation of such stress fields. Dynamic finite element simulations of FOD damage have also been correlated to such measurements. Evidence for relaxation of such stresses on fatigue cycling has been modeled and directly observed by *in situ* x-ray diffraction measurements.
- Large-crack threshold behavior in a polycrystalline Ni-base disk alloy has been characterized at 100 and 1000 Hz at 25º, 550º and 650ºC, involving effects of microstructure, frequency load ratio and temperature. Values of the measured fatigue thresholds have been correlated to the fracture surface roughness.
- Theoretical solutions for the crack-tip opening and crack-shear displacements controlling the growth of small fatigue cracks have been developed.
- New computational (finite-element) methods for 3-D simulations of fretting fatigue (*Fretting Fatigue Simulator*) have been developed using a ring-element approach.
- Through an analogy between the asymptotic fields at contact edges and ahead of a crack, a crack-analogue approach to contact fatigue (*Crack Analogue*) has been developed, and validated by experiment in Al and Ti alloys.

- A continuum level mechanics model (*Adhesion Model*), incorporating interfacial adhesion, material properties and contact loads, for predicting contact fatigue crack initiation for a variety of loading states and contact geometry, has been developed. The effect of roundness of a nominally sharp contact geometry on fretting fatigue crack initiation was investigated analytically and validated with experimental results on Ti-6Al-4V.
- Palliatives to fretting fatigue such as surface modifications through shot-peening, laser shock-peening and coatings on fretting fatigue damage are being explored.
- The influence of contact and bulk stresses, contact geometry, material microstructure and surface finish on the fretting fatigue behavior of Ti-6Al-4V has been investigated through controlled experiments, using the MURI-developed fretting fatigue device.
- A new framework for understanding the fundamentals of foreign object damage has been developed within the context of dynamic indentation.
- A new theoretical model for the fretting of coated metal surfaces has been developed which specifically addresses the role of plastic deformation of the metal substrate.

Research Objectives

This program is centered on the definition, microstructural characterization and mechanism-based modeling of the limiting states of damage associated with the onset of high-cycle fatigue failure in Ti and Ni-base alloys for propulsion systems. Experimental and theoretical studies are aimed at three principal areas: high cycle/low cycle fatigue (HCF/LCF) interactions, the role of notches, foreign object damage and fretting. The approach is to combine the characterization of microstructural damage with detailed micro-mechanical evaluation and modeling of the salient micro-mechanisms to facilitate the prediction of the effects of such damage on HCF lifetimes.

The primary study has been focused at ambient temperatures on Ti-6Al-4V, with a bimodal processed blade microstructure, and at higher temperatures on a fine-grained poly-crystalline Ni-base disk alloy; additional studies are being performed on Ti-6Al-4V with a lamellar microstructure. Specific objectives include: (a) systematic experimental studies to define crack formation and lower-bound fatigue thresholds for the growth of “small” and “large” cracks at high load ratios and high frequencies, in the presence of primary tensile and mixed-mode loading; (b) similar definition of lower-bound fatigue thresholds for crack formation in the presence of notches, fretting, or projectile damage, on surfaces with and without surface treatment (e.g., laser shock peened); (c) development of an understanding of the nature of projectile (foreign object) damage and its mechanistic and mechanical effect on initiating fatigue-crack growth under high-cycle fatigue conditions; (d) development of new three-dimensional computational and analytical modeling tools and detailed parametric analyses to identify the key variables responsible for fretting fatigue damage and failure in engine components, including the identification and optimization of microstructural parameters and geometrical factors and of surface modification conditions to promote enhanced resistance to fretting fatigue; (e) development of a mechanistic understanding for the initiation and early growth of small cracks in order to characterize their role in HCF failure, with specific emphasis on initiation at microstructural damage sites and on subsequent interaction of the crack with characteristic microstructural barriers. The ultimate aim of the work is to provide quantitative physical/mechanism-based criteria for the evolution of critical states of HCF damage, enabling life-prediction schemes to be formulated for fatigue-critical components of the turbine engine.

A. Mixed-Mode High-Cycle Fatigue Thresholds in Ti-6Al-4V (UCB)

The effect of mixed-mode (mode I+II) loading on the high-cycle fatigue thresholds has been studied in Ti-6Al-4V with a bimodal microstructure (~60% primary-α, ~40% lamellar $\alpha+\beta$). Specifically, the influence of crack size on such thresholds has been investigated for large (> 5 mm) and short (~200 μm) through-thickness cracks, and microstructurally-small (< 50 μm) surface cracks.

Large crack tests were conducted using the asymmetric four-point bend (AFPB) geometry [1], with load ratios, R of 0.1 to 0.8 being investigated for mode-mixities ranging from pure mode I (phase angle, $\beta = 0^o$ or $\Delta K_{II}/\Delta K_I = 0$) to nearly pure mode II ($\beta = 82^o$ or $\Delta K_{II}/\Delta K_I \sim 7.1$). Corresponding short crack thresholds were obtained using identical techniques, after carefully machining out the crack wake to within ~200 μm of the crack tip [2]. Small crack thresholds were determined using an inclined crack technique. A small, semi-elliptical surface pre-crack was first obtained by standard mode I, three-point bend testing at $R = 0.1$ (50 Hz) of wide (16.3 mm), 5 mm thick rectangular bars machined in the L-T orientation. Once a small crack had initiated, a bend bar was carefully machined from the original wide sample with the small crack inclined at the desired angle to the axis of the bar, which was then subjected to symmetric four-point bending for the threshold determination. Linear elastic solutions for the stress-intensity ranges for small semi-elliptical surface cracks in mode I and mixed-mode loading were obtained from the Newman-Raju [3] and He-Hutchinson [4] solutions, respectively.

Large crack thresholds: As observed previously in many metallic alloys (e.g., [5]), the fatigue threshold was seen to decrease with increasing load ratio (Fig. 1). In addition, a strong effect of mode-mixity was observed when the thresholds were characterized in terms of a single parameter, strain-energy release rate, ΔG (incorporating both mode I and mode II contributions to the crack-driving force) (Fig. 2). Moreover, the mode I threshold was found to be the *worst-case* condition, implying that the presence of a mixed-mode loading component does not negate the possibility of a threshold-based design methodology. However, by “correcting” for crack-tip shielding using a compliance-based technique developed as part of this initiative [6], the marked influence of mode-mixity (and load ratio) was reduced, implying that the major influence of mode-mixity in increasing the mixed-mode threshold is associated with mode II shielding by crack-surface interference, i.e., friction and interlock between crack-surface asperities [6].

Short crack thresholds: Short crack thresholds (Fig. 3), where the removal of the crack wake acts to markedly diminish the effect of crack-tip shielding, were found to be relatively independent of load ratio and mode-mixity, consistent with this reduced role of shielding. Indeed, the values of the short crack ΔG thresholds were similar to the corresponding “shielding-corrected” large crack values.

Small crack thresholds: ΔG thresholds for microstructurally-small surface cracks [7] were found to be substantially lower than thresholds for large cracks; in fact, up to 70-90 times lower (Fig. 4). In addition to the role of crack-tip shielding, biased sampling of “weak-links” in the microstructure by such small flaws becomes critical where their size is comparable to the scale of microstructure. As there is virtually no information in the literature concerning the mixed-mode behavior of such small flaws prior to these results, this would appear to be an important topic for further investigation.

B. Role of Foreign-Object Damage on HCF Thresholds in Ti-6Al-4V (UCB)

The objective of this study during the past year has been specifically to examine the roles of residual stresses and foreign-object damage (FOD) induced microcracks (~2 to 25 μm in surface length) on the earliest stages of FOD-induced high-cycle fatigue (HCF) failures in the bimodal Ti-6Al-4V alloy, α+β processed for typical turbine blade applications. This was achieved by defining the limiting conditions for crack initiation and early fatigue-crack growth in the presence of such microcracks, in comparison to the fatigue threshold behavior of naturally-initiated small (*2c* ~ 45-1000 μm) and large through-thickness (>5 mm) cracks in undamaged material.

Using high-velocity (200-300 m/s) impact of 1 or 3.2 mm steel spheres on the flat surface of fatigue test specimens (Fig. 5) to simulate FOD, it was found that the subsequent resistance to HCF was markedly reduced due to earlier crack initiation [8,9]. Premature crack initiation and subsequent near-threshold crack growth were primarily affected by the interplay of a number of factors, specifically (i) the stress concentration due to the FOD indentation, (ii) the creation (at highest impact velocities only) of microcracks at the crater rim of the damaged zone (Fig. 6), (iii) microstructural damage from FOD-induced plastic deformation, and (iv) the localized presence of tensile residual stresses [10,11] around the indent (Fig. 7).

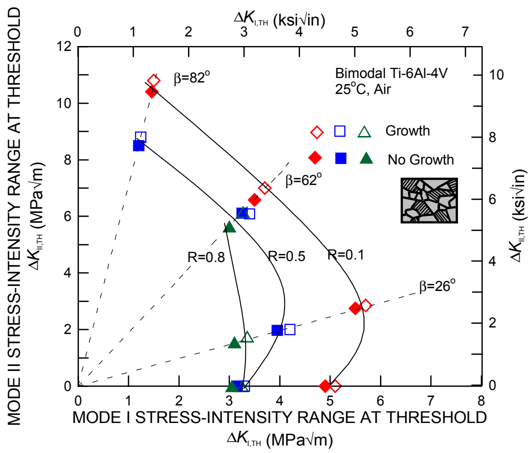

Fig. 1. Mixed-mode threshold envelopes for large (> 5 mm) through-thickness cracks in the bimodal microstructure (schematic in inset), with the mode II stress-intensity range at threshold, as a function of the mode I stress-intensity range at threshold.

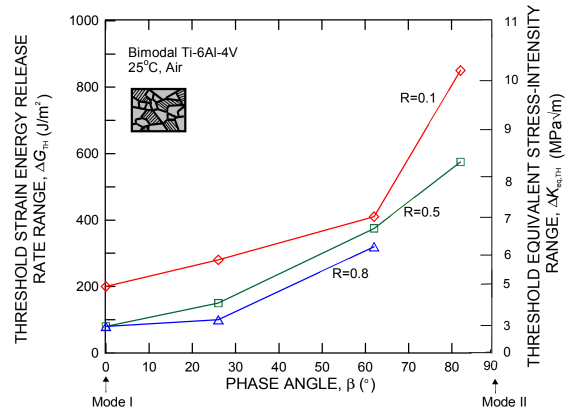

Fig. 2. The threshold strain-energy release rate, ΔG_{TH}, and equivalent stress-intensity range, $\Delta K_{eq,TH}$, are plotted as a function of phase angle, β, for large cracks subjected to mixed-mode loading at $R = 0.1$, 0.5 and 0.8.

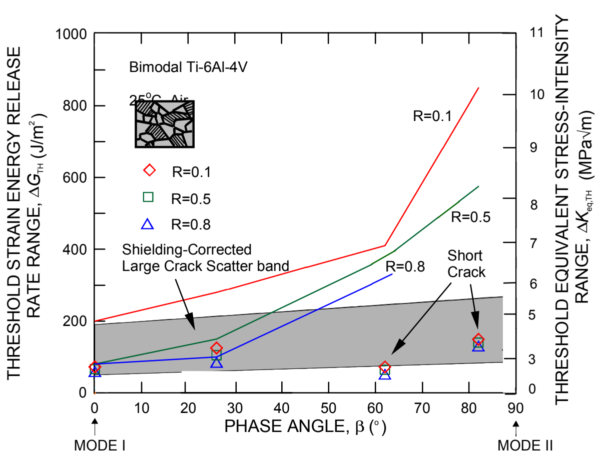

Fig. 3. Variation in the mixed-mode thresholds, ΔG_{TH}, as a function of phase angle, β, in the bimodal structure. Shown are results at three load ratios for large (> 5 mm) cracks, before and after "correcting" for crack-tip shielding, and for short (~200 µm) through-thickness cracks.

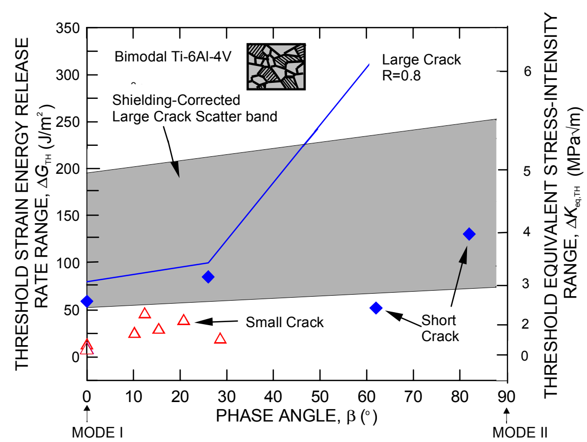

Fig. 4. Variation in the mixed-mode thresholds, ΔG_{TH}, as a function of phase angle, β, for small (< 50 µm) semi-elliptical surface cracks in the bimodal microstructure. Shown for comparison are results for short (~200 µm) through-thickness cracks and for large (> 5 mm) cracks under *worst-case*, high R conditions.

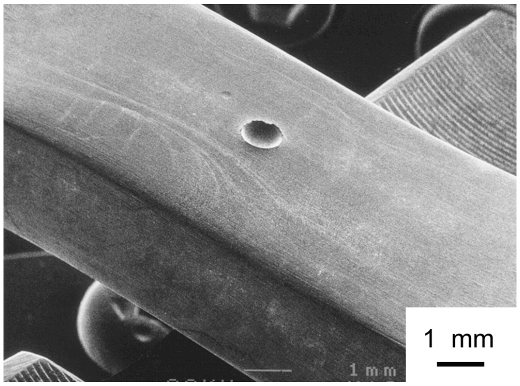

Fig. 5. Gauge section of modified K_B specimens for simulated FOD studies after high-velocity 300 m/s impact using 1.0 mm diameter steel sphere (normal impact angle)

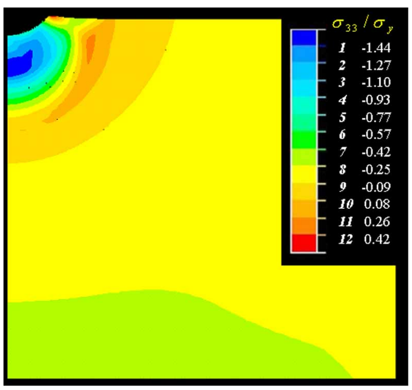

Fig. 7. Residual stress distribution in plane perpendicular to longitudinal axis of K_B specimen, after 300 m/s impact using 1 mm steel shot. After Chen and Hutchinson. σ_{33} = residual stress in longitudinal direction, σ_y = yield stress (915 MPa)

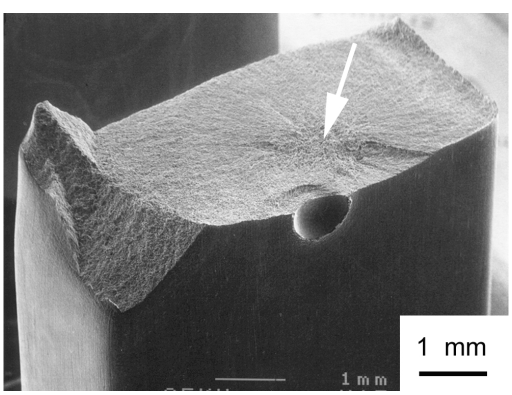

Fig. 9. Lower stress fatigue loading after 300 m/s impact using 1 mm diameter steel shot caused crack initiation away from the indent site (marked by arrow): nominally applied σ_{max} = 325 MPa, R = 0.1, N_F = 1.3 x 10^8 cycles

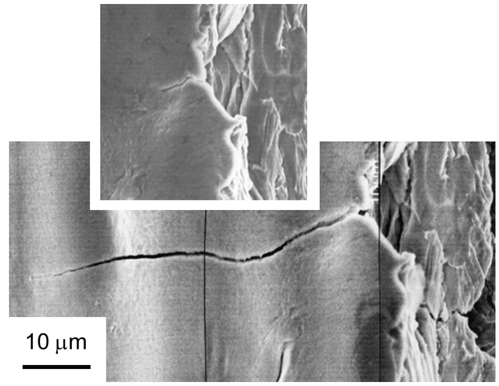

Fig. 6. SEM micrograph of fatigue crack that formed at FOD-induced microcrack (small inserts). 3.2 mm steel shot, 300 m/s impact velocity. Nominally applied σ_{max} = 500 MPa, R = 0.1, N = 29,000 cycles

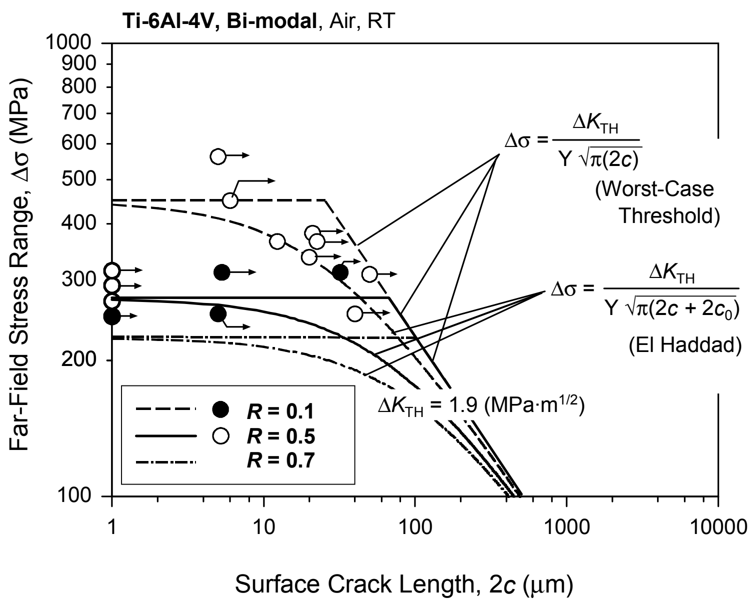

Fig. 8. Modified Kitagawa-Takahashi diagram representing the threshold crack-growth conditions (da/dN = 10^{-11}-10^{-10} m/cycle) at R = 0.1 and 0.5 for FOD-induced small-cracks in bimodal Ti-6Al-4V (300 m/s, 3.2 mm steel shots). Plotted is the threshold stress range as a function of surface crack length. Data points are corrected for the stress concentration of the FOD indents.

Specifically, the magnitude of the residual stresses in the vicinity of the damage sites were computed numerically and experimentally measured using synchrotron x-ray micro-diffraction studies. Prior to fatigue cycling, peak tensile values of these residual stresses were of the order of 300 MPa and were located in the interior adjacent to the highly deformed region beneath the indentations [10,11] (Fig. 7).

Two groups of FOD-induced HCF failures could be identified. The first group involved fatigue crack initiation directly at the impact site and caused failures within 10^5 to 10^6 cycles. The proposed criteria for such failures was described by a modified Kitagawa-Takahashi approach, where the limiting threshold conditions are defined by the stress-concentration corrected smooth-bar fatigue limit (at microstructurally-small crack sizes) and a "worst-case" fatigue crack growth threshold (at larger "continuum-sized" crack sizes) as shown in Fig. 8 [9].

The second group of failures at 10^7 to 10^8 cycles was found to initiate at locations remote from impact damage in regions of high tensile residual stresses (Fig. 9). It was found that simple superposition of the initial tensile residual stresses onto the applied stresses provided a significant contribution to the reduction in fatigue strength by affecting the local mean stress and load ratio. Accordingly, the modified Kitagawa-Takahashi approach proposed above was corrected for the presence of tensile residual stresses to account for such failures (also shown in Fig. 8). With this correction, the approach provides a rational basis for the effect of foreign-object damage on high cycle fatigue failures in Ti-6Al-4V [10].

C. Residual Stresses associated with FOD-Induced HCF Behavior in Ti-6Al-4V (UCB)

To better understand the driving force for fatigue-crack initiation and propagation associated with sites of foreign object damage, the residual stress and strain gradients were assessed using a synchrotron-based spatially-resolved polycrystalline x-ray diffraction technique. The spatial resolution of this technique was 300-500 μm, limited at least in part by the size of the grains in the sample. The observed residual stress field was compared to both numerical predictions (by Chen and Hutchinson [10]) and experimental fatigue behavior (by Peters and Ritchie [8,9]). In all studies, foreign-object damage was simulated by firing a Cr-hardened steel sphere at velocities of 200-300 m/s onto the flat surface of a Ti-6Al-4V specimen in the bimodal (STOA) microstructure.

Residual stresses at damage sites: Consistent with the numerical predictions, spatially-resolved synchrotron x-ray diffraction measurements indicated the presence of a region of compression at the crater floor, and a region of tension und at the crater rim,. While the shape of the resulting strain gradients was qualitatively quite similar between the experimental observations and the numerical predictions, there were some notable discrepancies in the magnitude of the stresses [11]. Most specifically, the quasi-static analysis of Chen and Hutchinson [10] was insufficient to capture the observed residual stresses formed by dynamic impact, especially at the highest impact velocity of 300 m/s where the discrepancy was >500 MPa at both the floor and rim of the crater. Modifications to the numerical model incorporated the dynamic effects of strain-rate sensitivity, the inertial effect, and elastic wave interactions. The results of the dynamic model were very similar to experimental observations. Remnant discrepancy at the crater rim of 300 MPa may be attributable to the presence of microcracking and inhomogeneous deformation that were not captured in the numerical model.

The spatially-resolved diffraction studies also revealed that the most substantial plasticity (as estimated by Bragg peak broadening) was present at the crater rim, and the crater floor showed a slightly lower degree of plasticity.

Stability of the residual stress state during fatigue loading: Using *in situ* x-ray diffraction studies during cyclic loading, it was found that there was as much as a 50% reduction in the residual stress component along the direction of loading during the first cycle at the smooth-bar fatigue limit, i.e., at σ_{max} = 500 MPa (Fig. 9). The transverse stresses perpendicular to the load axis showed a ~20% reduction during the first cycle. After the first cycle, there was no substantial decay of residual stresses as a function of the logarithm of the number of cycles (out to 1000 cycles). The threshold stress for first-cycle relaxation under the current conditions was between 325 and 500 MPa, as there was no observed relaxation at 325 MPa. The numerical model of Chen and Hutchinson was modified to incorporate the observed cycle-dependent reduction in the yield strength during reversed loading (Bauschinger effect). This model showed a ~40% reduction in stresses at the crater floor during the first cycle and no subsequent relaxation, largely consistent with the observed behavior.

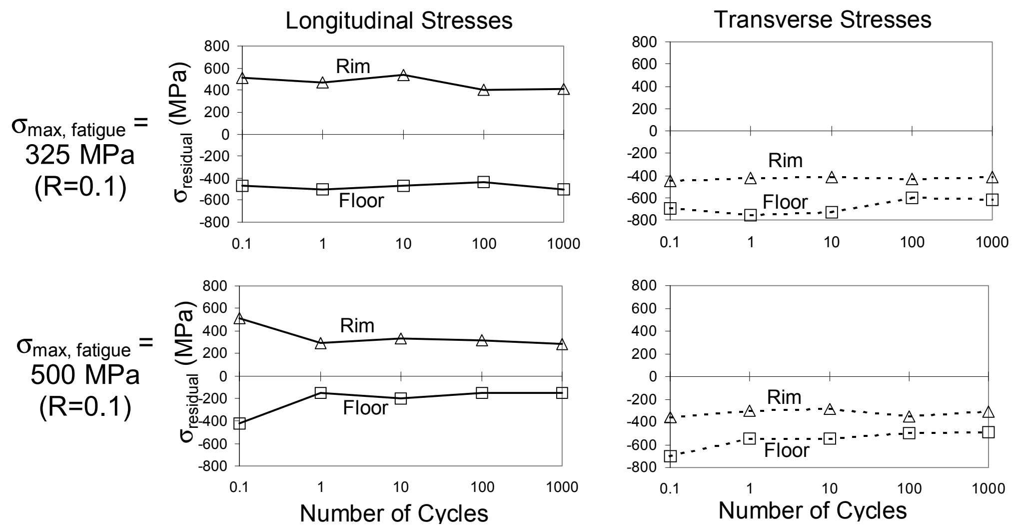

Fig. 9. Fatigue loading can cause a reduction in the residual stress state at the rim and base (floor) of a hemispherical damage site (quasi-static indentation loading, indenter diameter = 3.2 mm, crater diameter = 2.05 mm, crater depth = 0.30 mm). Longitudinal stresses are along the direction of loading and transverse stresses are perpendicular to the direction of loading. Based on the four graphs, relaxation occurs only at fatigue stresses σ_{max}>325 MPa, and relaxation occurs almost entirely during the first cycle.

Relevance to impact-induced fatigue failures: In many of the cases considered in this study, the initial residual stress state was of little importance in assessing the location of crack formation due to fatigue loading. At high applied stresses, the initial residual stress state was reduced substantially during fatigue loading. But more importantly, the presence of microcracks at the crater rim, as well as the high stress concentration factor at the crater floor were the primary factors influencing the onset of failure. However, at low applied fatigue stresses (σ_{max}=325 MPa), crack formation was often found to occur at the side of the K_B tensile specimens due to the presence of high tensile residual stresses (determined both experimentally and by numerical modeling) and the lack of crack-mitigating plasticity.

As noted above, the Kitigawa-Takahashi diagram proved to be a useful approach to predict the critical conditions for failure by incorporating both the fracture-mechanics based fatigue threshold (in the worst-case limit) and the stress-based fatigue limit. This approach can account for the contributions of both the stress concentration factor and the presence of microcracks. Moreover, in cases where residual stresses are significant, the alteration in stress ratio ($\sigma_{min}/\sigma_{max}$)

caused by the superposition of the residual stresses can also be captured to predict conditions of safe operation [10].

D. Theoretical Modeling of High-Cycle Fatigue (Harvard)

Foreign-object damage: As noted above, extensive modeling was performed on various aspects of foreign object damage (FOD) as it relates to the fatigue life of turbine blades; this was coordinated with the experimental Berkeley effort described above [10,11]. Specific aspects of the problem that were investigated included (a) dynamic effects in FOD determination, (b) specimen size effects, (c) influence of inclined versus normal impacts, and (d) residual stress relaxation at FOD sites due to subsequent cyclic stressing.

Most of the discrepancy between the theoretical results for residual stress at FOD sites and the experimental data obtained by the Berkeley group could be accounted for by inclusion of dynamic effects (inertia and material strain-rate sensitivity), combined with a more realistic representation of the beam-like geometry of the Berkeley specimens. The major goal of the research of demonstrating the ability to predict indent geometry and residual stress due to prescribed FOD impacts was thus largely achieved. Under subsequent cyclic stressing, both the stress concentration due to the geometry change and the residual stresses influence fatigue-crack growth. The theoretical results from the FOD analysis were used to assess the effect of FOD level on critical crack size for threshold fatigue-crack growth. For sufficiently deep indents, it was shown that the stress concentration due to FOD is the dominant factor.

Another aspect where theory and experiment were brought into agreement was in connection with the role of residual stress relaxation at the bottom of the indent in the first few cycles of cyclic stressing following FOD. The Berkeley group obtained stress-strain data for cyclic stressing which provided quantitative constitutive input for the numerical simulation. The key to the relaxation is the Bauschinger effect under reversed loading. The computed relaxation results were in reasonably good agreement with the experimental measurements. The effect is significant because relaxation of the residual stress at the FOD site changes the effective R-value experienced by a putative fatigue crack at that location.

Interactions associated with small fatigue-crack growth: A study on the interactions of fatigue cracks with elastic obstacles, which grew out of the visit to Harvard of Dr. C. W. Wang of the Aeronautical Research Laboratory of Australia, was completed. This work extends the earlier work on small cracks by Hutchinson and Tvergaard [13].

E. High-Cycle Fatigue of Nickel-Base Superalloys (Mich. Tech.)

The fatigue-crack propagation behavior of a nickel-base superalloy was also evaluated at ambient and elevated temperatures over a range of frequencies and load ratios. Interesting effects of microstructure and frequency on the fatigue thresholds, unlike those predicted from the literature, have been explored in detail. Most effort has been directed at characterizing fracture surface morphologies, and to conduct transmission electron microscopy (TEM) studies of deformation mechanisms relevant to plastic-zone deformation. Crack-closure effects have also been evaluated to try to elucidate the relative contributions of extrinsic and intrinsic mechanisms in determining the fatigue-crack propagation thresholds.

Two different microstructural conditions of KM4, a nickel-base turbine disk alloy, have been studied, namely a coarse- (~ 60 μm) and a fine-grained (~ 6 μm) microstructure. Details are given in ref. [14]. Fatigue-crack propagation thresholds were measured at 100 and 1,000 Hz, at room temperature, 550°C, and 650°C, and at load ratios of R = 0.4 and 0.7, conditions that simulate those seen in turbine disks.

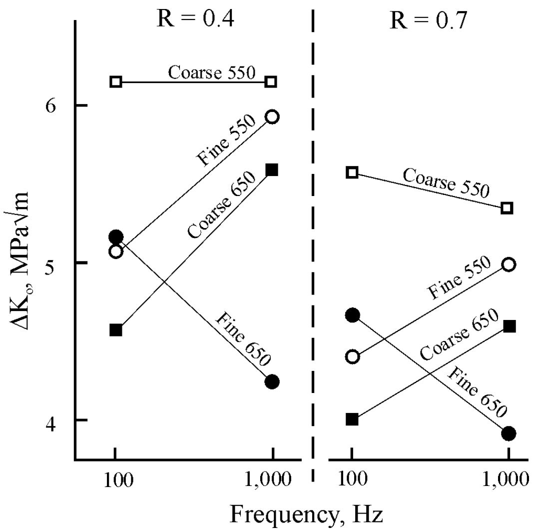

Fig. 10. Fatigue-crack propagation thresholds in KM4 at several temperatures, frequencies, microstructures and load ratios.

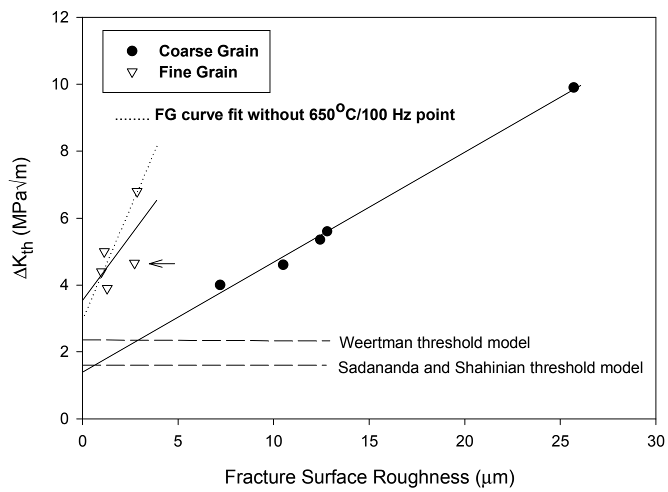

Fig. 11. Relationship between fracture surface roughness and fatigue-crack propagation threshold, for three temperatures, two load ratios, two microstructures and two frequencies, showing excellent correlation. Intersection of the curves extrapolated to zero roughness results in a good match between theoretical and measured threshold values.

Fig. 10 shows a summary of the fatigue-crack propagation thresholds obtained at high temperature for KM4 nickel-base superalloy. The only trend that is clearly evident is that of load ratio; as R increases, the curves all shift down to lower thresholds. Nothing else is clear simply from these data. For example, for the fine-grain material, the threshold increases with frequency at 550°C but decreases with frequency at 650°C. Effects of other variables are also unclear.

Quantitative stereo-fractography was conducted in the scanning electron microscope, and based on these studies an interesting correlation was found between fracture surface roughness and HCF threshold. As shown in Fig. 11, when all the data are plotted in the form of threshold values vs. the near-threshold fracture-surface roughness, a very good fit is obtained.

Measurements of the magnitude of the crack closure present at load ratios between 0.3 and 0.7 are currently in progress. To date, no measurable evidence of crack closure has been found at load ratios above about 0.5 (depending on the microstructure). Therefore, while closure is present at load ratios of 0.3 and 0.4, it cannot explain all the variations in the data. Current studies are directed at exploring and modeling the interactions between intrinsic deformation mechanisms, extrinsic factors such as closure, and the fatigue-crack propagation threshold.

F. Modeling and Experimental Studies of Fretting Fatigue (MIT)

Through a combination of analytical modeling, numerical simulations and controlled experimentation, the overall objective of this part of the program has been to investigate fretting fatigue, a complex multi-stage, multi-axial, fatigue-fracture phenomenon involving fatigue crack initiation, initial small crack propagation and crack arrest or subsequent long crack propagation, ultimately leading to structural failure due to mechanical overload. Recognizing that fretting fatigue is strongly influenced by the contact conditions of which the contact geometry provides a natural metric for classification, two bounds were identified – the sharp-edged contact and the spherical contact. Sharp-edged contacts have been analyzed analytically using the crack analogue methodology [15], while the spherical contacts were modeled using finite elements [16] and investigated experimentally [17,18] and modeled analytically [19]

"Notch analogue" model for fretting fatigue [20]: The effect of roundness of a nominally sharp contact geometry on fretting fatigue crack initiation was investigated. Using analytical and numerical finite element methods, the asymptotic forms for the stress fields in the vicinity of a rounded punch-on-flat substrate were derived for both normal and tangential contact loading conditions. By examining the similarities between the asymptotic stress fields for the sharply rounded flat punch contact and those around the tip of a blunt crack, a "notch analogue" model for fretting fatigue crack initiation was developed. The analysis showed that the maximum tensile stress that occurs at the edge of the contact is proportional the mode II stress-intensity factor of a sharp punch weighted by a geometric factor related to the roundness of the punch. Conditions for crack initiation were then derived through a comparison of the maximum tensile stress at the edge of the fretting contact and the plain fatigue endurance limit of the material.

Fretting fatigue experiments [21]: A systematic investigation of the fretting fatigue behavior of the titanium alloy Ti-6Al-4V in both the mill-annealed and the solution treated and overaged (STOA) microstructure, was carried out using a sphere-on-flat fretting fatigue device that facilitated real-time, control and monitoring of all the relevant parameters such as the contact geometry, contact (normal and tangential) loads and the bulk alternating stress. While three sets of experiments were conducted to examine the influence of the bulk stress, the tangential load and the normal load, respectively, on fretting fatigue response, the effect of microstructure on fretting fatigue was explored briefly with experiments on acicular, Widmanstätten, and martensitic Ti-6Al-4V.

The important results from these studies can be summarized as follows:

1. In the experiments where the contact loads were maintained constant while the bulk stress was varied, fretting reduced the fatigue strength of Ti-6Al-4V, with the strength reduction factor being higher for those experiments with a constant but higher tangential load compared to those with a constant but lower tangential load.

2. For cases where the bulk stress and the normal loads were maintained constant, the total life to failure of the fretted materials was reduced as the tangential load increased, the reduction in life being larger for the experiments with the lower fretting pad radius.

3. In the experiments where the bulk stress and the tangential loads were maintained constant, the total life to failure of the fretted materials increased as the normal load increased, the increase in life being larger for the experiments with the larger fretting pad radius.

4. With the exception of the martensitic structure which displayed enhanced fretting fatigue resistance, the other microstructures did not exhibit any significant improvement in fretting fatigue resistance, compared to the basic STOA or the mill-annealed microstructure.

5. Using the measured maximum static friction coefficient of 0.95 for Ti-6Al-4V, the experimentally observed contact and stick-zone radii exhibited good agreement with analytical predictions.

6. The adhesion model predictions concerning strength of adhesion (weak) and crack initiation were validated with experimental observations of stick-slip behavior and fretting fatigue failures, respectively.

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V. Tvergaard	Collaborator, Technical University of Denmark, Lyngby, Denmark

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48. P. R. Birch, "A Study of Fretting Fatigue in Aircraft Components", *M.S. Thesis*, Department of Materials Science and Engineering, MIT, June 1998 (supervisor: S. Suresh).
49. C. Chenut, "Fretting Fatigue at Rounded Corners", *Engineering Diplome Thesis*, Ecole Polytechnique, France, (completed at MIT), Sept. 1998 (co-supervisor: S. Suresh).
50. B. L. Boyce, "High Cycle Fatigue Thresholds in a Turbine Engine Titanium Alloy", *M.S. Thesis*, Department of Materials Science and Mineral Engineering, University of California at Berkeley, Dec. 1998 (supervisor: R. O. Ritchie).
51. B. L. Boyce, "Understanding Impact-Induced Fatigue Failure", *Ph.D. Thesis,* Department of Materials Science and Engineering, University of California at Berkeley, expected May 2001 (supervisor: R. O. Ritchie).
52. J. P. Campbell, "Mixed-Mode Fatigue-Crack Growth in Ti-6Al-4V", *Ph.D. Thesis*, Department of Materials Science and Mineral Engineering, University of California, Berkeley, Dec. 1999 (supervisor: R. O. Ritchie).
53. R. K. Nalla, "Small-Crack Mixed-Mode High-Cycle Fatigue Thresholds in Ti-6Al-4V", *M.S. pending*, Department of Materials Science and Engineering, University of California at Berkeley, expected Aug. 2002 (supervisor: R. O. Ritchie).
54. G. Kirkpatrick, "Fretting Fatigue Analysis and Palliatives", *M.S. Thesis*, Department of Materials Science and Engineering, MIT, June 1999 (supervisor: S. Suresh).
55. B. P. Conner, "Mechanical and Microstructural Effects on Fretting Fatigue in Ti-6Al-4V", *M.S. Thesis*, Department of Materials Science and Engineering, MIT, June 2000 (supervisor: S. Suresh).
56. L. Chambon, "Palliatives and Life Prediction Methodologies in Fretting Fatigue", *M.S. pending*, Department of Materials Science and Engineering, MIT, expected Feb. 2001 (supervisor: S. Suresh).
57. Xi. Chen, "Foreign Object Damage and Fracture Cracking", *Ph.D. Thesis*, Division of Applied Sciences, Harvard University, June 2001 (supervisor: J. W. Hutchinson).

58. S. Marras, "Mechanics Studies of Fatigue Crack Propagation Thresholds", *M.S. Thesis*, Department of Mech. Engineering, Michigan Technological University, Dec. 1999 (supervisor: W. W. Milligan).
59. S. A. Padula II, "High Frequency Fatigue of Nickel-Base Superalloys", *Ph.D. pending*, Department of Metallurgical and Materials Engineering, Michigan Technological University, expected May 2002 (supervisor: W. W. Milligan).
60. A. Shyam, "Fatigue Mechanisms in Nickel-Base Superalloys", *Ph.D. pending*, Department of Metallurgical and Materials Engineering, Michigan Technological University, expected May 2002 (supervisor: W. W. Milligan).

Other Publications

61. B. L. Boyce and R. O. Ritchie, "Lower-Bound Thresholds for Fatigue-Crack Propagation under High-Cycle Fatigue Conditions in Ti-6Al-4V," in *Proceedings of the Third National Turbine Engine High Cycle Fatigue Conference*, W. A. Stange and J. Henderson, eds., Universal Technology Corp., Dayton, OH, CD-Rom, 1998, CD-Rom, session 5, pp. 11-18.
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65. S. A. Padula II, A. Shyam, D.L. Davidson and W.W. Milligan, "High Frequency Fatigue of Nickel-Base Superalloys", in *Proceedings of the Fourth National Turbine Engine High Cycle Fatigue (HCF) Conference,* J. Henderson, ed., Universal Technology Corp., Dayton, OH, CD-Rom, 1999, CD-Rom, session 2, pp. 22-28.
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67. J. P. Campbell, A. W. Thompson and R. O. Ritchie, "Mixed-Mode Crack-Growth Threshold In Ti-6Al-4V under Turbine-Engine High-Cycle Fatigue Loading Conditions", in *Proceedings of the Fourth National Turbine Engine High Cycle Fatigue (HCF) Conference,* J. Henderson, ed., Universal Technology Corp., Dayton, OH, CD-Rom, 1999, CD-Rom, session 2, pp. 41-49.
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69. B. L. Boyce, O. Roder, A. W. Thompson, and R. O. Ritchie, "Measurement of Residual Stresses in Impact-Damaged Ti-6-4 Specimens", in *Proceedings of the Fourth National Turbine Engine High Cycle Fatigue (HCF) Conference,* J. Henderson, ed., Universal Technology Corp., Dayton, OH, CD-Rom, 1999, CD-Rom, session 10, pp. 28-40.
70. O. Roder, J. O. Peters, A. W. Thompson, and R. O. Ritchie, "Influence of Simulated Foreign Object Damage on the High Cycle Fatigue of a Ti-6Al-4V Alloy for Gas Turbine Blades", in *Proceedings of the Fourth National Turbine Engine High Cycle Fatigue (HCF) Conference,* J. Henderson, ed., Universal Technology Corp., Dayton, OH, CD-Rom, 1999, CD-Rom, session 10, pp. 41-50.
71. J. O. Peters, B. L. Boyce, A. W. Thompson, and R. O. Ritchie, "Role of Foreign-Object Damage on High-Cycle Fatigue Thresholds in Ti-6Al-4V", in *Proc. 5th National Turbine Engine High Cycle*

Fatigue Conf., M. J. Kinsella, ed., Universal Technology Corp., Dayton, OH, 2000, CD-Rom, session 1, pp. 28-37.
72. J. P. Campbell and R. O. Ritchie, "Mixed-Mode High-Cycle Fatigue Thresholds in Turbine Engine Ti-6Al-4V", in in *Proc. 5th National Turbine Engine High Cycle Fatigue Conf.,* M. J. Kinsella, ed., Universal Technology Corp., Dayton, OH, 2000, CD-Rom, session 7, pp. 35-44.
73. S. A. Padula, II, A. Shyam, and W. W. Milligan, "High Temperature, High Cycle Fatigue of Nickel-Base Turbine Disk Alloy," in *Proc. 5th National Turbine Engine High Cycle Fatigue Conf.,* M. J. Kinsella, ed., Universal Technology Corp., Dayton, OH, 2000, CD-Rom, session 7, pp. 54-61.
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75. A. Shyam, S.A. Padula II and W.W. Milligan, "High Temperature, High Cycle Fatigue of a Nickel-Base Turbine Disk Alloy", in *Proc.6th National Turbine Engine High Cycle Fatigue Conf.,* M. J. Kinsella, ed., Universal Technology Corp., Dayton, OH, 2001, CD-Rom, section 8.
76. J. O. Peters, B. L. Boyce, J. M. McNaney, X. Chen, J. W. Hutchinson, and R. O. Ritchie, "Foreign-Object Damage and High-Cycle Fatigue in Ti-6Al-4V", in *Proc.6th National Turbine Engine High Cycle Fatigue Conf.,* M. J. Kinsella, ed., Universal Technology Corp., Dayton, OH, 2001, CD-Rom.
77. B. L. Boyce, X. Chen, J. W. Hutchinson, and R. O. Ritchie, "FOD Characterization by Mesoscale Synchrotron X-Ray Diffraction", in *Proc.6th National Turbine Engine High Cycle Fatigue Conf.,* M. J. Kinsella, ed., Universal Technology Corp., Dayton, OH, 2001, CD-Rom, section 8.

Awards Received

R. O. Ritchie was awarded the TMS 1996 Distinguished Materials Scientist/Engineer Award.
S. Suresh was elected Fellow of the American Society of Mechanical Engineers, 1996.
S. Suresh was elected Honorary Member of the Materials Research Society of India, 1996.
R. O. Ritchie was awarded the Distinguished Van Horn Lectureship at Case Western Reserve University, Cleveland, OH, 1996-97.
S. Suresh was awarded Swedish National Chair in Engineering (1996-98), for nine months leave at the Royal Institute of Technology, Stockholm.
S. Suresh, Outstanding Alumnus Award, Indian Institute of Technology, Madras, Fall 1997.
P. Pallot was awarded the best research project Award by Ecole Polytechnique, Sept. 1997.
R. O. Ritchie was awarded a Southwest Mechanics Lectureship, 1997-1998.
R. O. Ritchie was awarded the Most Outstanding Paper Award in 1998 from ASTM *Journal of Testing and Evaluation*.
R. O. Ritchie presented the C. J. Beevers Memorial Lecture at the Seventh International Fatigue Congress, Beijing, June 1999.
S. Suresh was elected Fellow of TMS, Fellow Class of 2000.
S. Suresh was offered Clark Millikan Endowed Chair at Cal. Tech.- sabbatical leave 1999-2000.
S. Suresh was awarded the TMS 2000 Distinguished Materials Scientist/Engineer Award.
R. O. Ritchie was elected to the National Academy of Engineering, 2001.
W. W. Milligan received Michigan Tech's *Research Award* for 2001
B. L. Boyce was awarded Hertz Foundation Fellowships for research at Berkeley, 1996-2001
P. Birch was awarded a NSF Graduate Fellowship for research at MIT.

Transitions

B. L. Boyce and R. O. Ritchie, W. W. Milligan, and B. Conner (for S. Suresh), all attended, participated in government/industry/university meetings, and presented four papers at the *Sixth National Annual Coordination Conference on High-Cycle Fatigue*, Jacksonville, FL, Feb. 2000. Members of the MURI have maintained close contact with relevant personnel at GE, Pratt & Whitney, Southwest Research and Wright Patterson AFB.