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 and to develop 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 on a polycrystalline Ni-base disk alloy. Notable highlights during the fourth year include the characterization and quantitative modeling of fretting and FOD and the definition of the role of mixed-mode loading on HCF thresholds in Ti-6Al-4V. Accomplishments are outlined below:

- Worst-case fatigue threshold stress intensities have been measured in STOA 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 and short cracks have been measured in Ti-6Al-4V, with both STOA and lamellar microstructures. Mixed-mode short-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 STOA 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 a quasi-static analytical model; predictions are being 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.
- Large-crack threshold behavior in a polycrystalline Ni-base disk alloy has been characterized at 100 and 1000 Hz at 25º, 550º and 650ºC, such that effects of microstructure, frequency load ratio and temperature were established.
- 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 focused 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 is focused both 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.

Lower-Bound HCF Thresholds (Mode I and Mixed-Mode) in Ti-6Al-4V (UCB)

In view of the extremely high frequencies (>1 kHz) involved, appropriate design against high cycle fatigue (HCF) failures invariably will be based on the concept of a threshold for fatigue-crack propagation, specifically characterized for HCF conditions, such as high load ratios, high frequencies and small crack sizes [1,2]. In this study, the near-threshold crack-growth rate behavior of large (>5 mm) cracks tested under both constant-R and constant-K_{max} conditions was evaluated in the bimodal Ti-6Al-4V microstructure. Large crack behavior was compared to that of naturally-initiated small (~45–1000 μm) cracks, and small (<500 μm) surface cracks initiated from sites of simulated foreign object damage (FOD). The specific objective was to discern whether "worst-case" threshold values, measured for large cracks, can have any utility as a *practical* lower bound for the onset of small-crack growth under HCF conditions. The high load ratio, large-crack tests are designed to eliminate crack closure mechanisms, thereby simulating the behavior of small cracks that are larger than microstructural dimensions but do not have a developed wake, i.e., for "continuum-sized" cracks.

The alloy used for all experiments was a 6.30Al, 4.17V, 0.19Fe, 0.19O, 0.13N, bal. Ti (wt%) alloy, supplied as 20 mm thick forged plates from Teledyne Titanium after solution treating for 1 hr at 925°C and vacuum annealing for 2 hr at 700°C. The microstructure consisted of a bimodal distribution of ~60 vol% primary-α and ~40 vol% lamellar colonies of $\alpha+\beta$, with a UTS of 970 MPa, a yield strength of 930 MPa and a Young's modulus of 116 GPa [3]. To minimize residual machining stresses, all samples were low-stress ground and chemically milled.

Effect of frequency: A comparison of fatigue-crack growth behavior between 50 Hz and 20,000 Hz in ambient air (including results from refs. [4,5], shown in Fig. 1, indicates no effect of frequency at near-threshold levels. Such frequency-independent growth rates in Ti alloys have also been reported for 0.1–50 Hz [6,7]; the current work extends this observation to beyond 1000 Hz. This result is particularly interesting in light of the significant accelerating effect of ambient air on fatigue crack growth when compared to behavior in vacuum. Davidson *et al.* have shown that growth rates *in vacuo* (10^{-6} torr) are ~2 orders of magnitude slower than in air at an equivalent ΔK, although the non-propagation threshold remains roughly the same. This apparent discrepancy is most likely an indication that the rate-limiting step of the environmental (air) effect goes to completion in <1 ms.

Effect of load ratio: Constant-R fatigue crack propagation at four load ratios (50 Hz) are compared to constant-K_{max} data at four K_{max} values: K_{max} = 26.5, 36.5, 46.5, and 56.5 MPa√m (1000 Hz) in Fig. 2. As expected, higher load ratios induce lower ΔK_{th} thresholds and faster growth rates at a given applied ΔK. The role of load ratio is commonly attributed to crack closure [8-10]. Based on compliance measurements, no closure was detected above R = 0.5; however, at R = 0.1-0.3, K_{cl} values were roughly constant at ~2.0 MPa√m. The measured variation of ΔK_{th} and $K_{max,th}$ values with R are compared in Figs. 3a,b and the variation of ΔK_{th} with $K_{max,th}$ is shown in Fig. 3c. The transition apparent in Figs. 3a-c is consistent with the observed closure level ~2 MPa√m (based on the elimination of closure above the transition as observed in the data of Schmidt and Paris [9]).

Worst-case threshold concept: To examine whether the very high load ratio thresholds, measured on large cracks in the apparent absence of crack closure effects, can be considered as "worst-case" thresholds for "continuum-sized" cracks, the high load-ratio fatigue-crack propagation data are compared to fatigue behavior from naturally initiated small cracks (~45–1000 μm) and small cracks (<500 μm) emanating from sites of foreign object damage; in both cases crack growth is not observed below ΔK ~ 2.9 MPa√m, Fig. 4 (details described in [11]). The present results show that with constant-K_{max} cycling at 1 kHz, a "worst-case" threshold can be defined in Ti-6Al-4V at ΔK_{TH} = 1.9 MPa√m (R ~ 0.95). Consequently, it is believed that the "worst-case" threshold concept can be used as a *practical* lower bound for the stress intensity required for the onset of small-crack growth under HCF conditions, provided crack sizes exceed microstructural dimensions.

Effect of mixed-mode loading: This approach is also applicable under mixed-mode conditions. Mixed-mode (I + II) fatigue-crack growth thresholds, for mode-mixity $\Delta K_{II}/\Delta K_I$ values from 0 (pure mode I) to 7.1, have been measured in the bimodal Ti-6Al-4V blade alloy microstructure at 1000 Hz and are shown in Fig. 5. The measured values of ΔK_I and ΔK_{II} at threshold have been used to construct mixed-mode threshold envelopes for load ratios ranging from R = 0.1 to 0.8. While the mode I threshold, $\Delta K_{I,TH}$, can be reduced with increasing applied phase angle ($\beta = \tan^{-1}(\Delta K_{II}/\Delta K_I)$), characterization of the mixed-mode threshold behavior in terms of the limiting strain-energy release rate range, ΔG_{TH}, indicates that the threshold increases monotonically with β, such that the threshold measured in pure mode I represents the worst-case condition. Consequently, for this alloy, the existence of mixed-mode loading should not preclude the use of a threshold-based fatigue-crack growth design methodology. In fact, this strongly suggests that, for continuum-sized cracks, pure mode I thresholds (*defined in terms of* ΔG) may be used as a conservative estimate of the mixed-mode threshold [11].

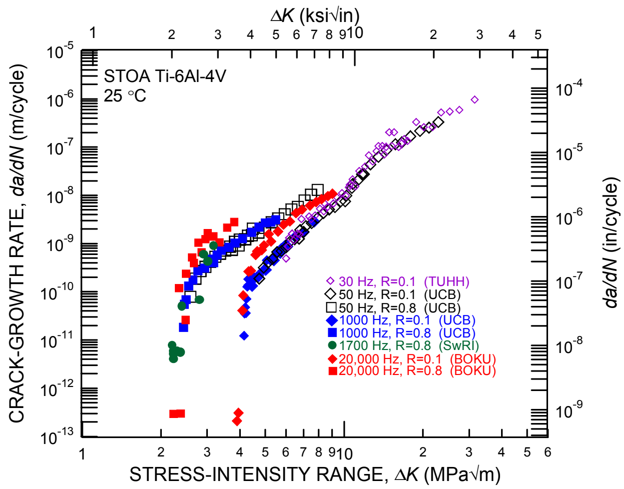


Figure 1. Effect of frequency on fatigue-crack growth in bimodal Ti-6Al-4V in room air. Results at 50 to 1000 Hz at UCB are compared to data on the same material at 30 Hz collected by Hines, Peters, and Lütjering [8] (TUHH), at 1500 Hz collected by Davidson [12] (SwRI), and at 20,000 Hz collected by Mayer and Stanzl-Tschegg [13] (BOKU). While there may be a slight shift in the Paris regime between 1000 Hz and 20,000 Hz, near-threshold behavior appears to be unaffected by frequency.

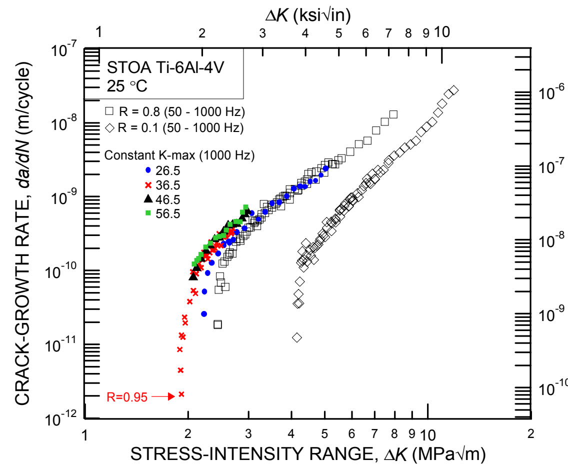


Figure 2. Constant-K_{max} fatigue crack propagation behavior at four different K_{max} values: K_{max} = 26.5, 36.5, 46.5, and 56.5 MPa√m (1000 Hz) compared to constant-R data at R = 0.1 and 0.8 (50-1000 Hz), in bimodal Ti-6Al-4V, showing the definition of worst-case thresholds for "continuum-sized" cracks.

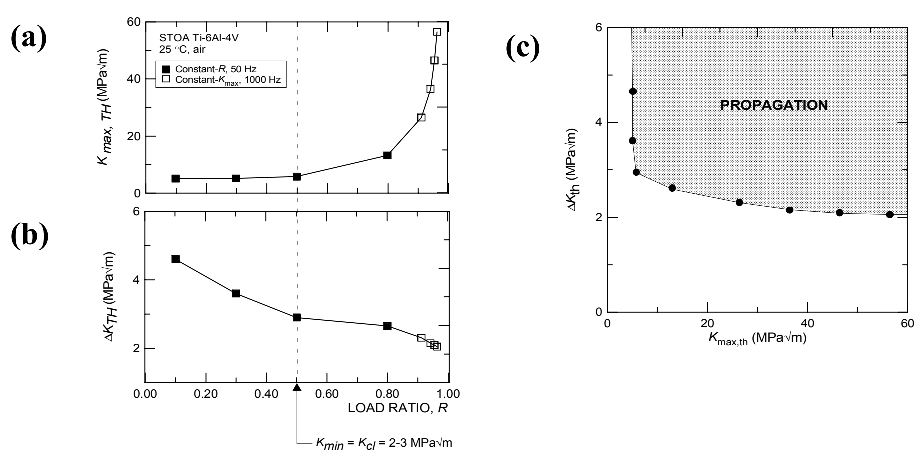


Figure 3. Combinations of (a) K_{max}-R, (b) ΔK-R, and (c) ΔK-K_{max} required for "threshold": growth at 10^{-10} m/cycle. As suggested by Schmidt and Paris [9], the closure mechanism would cause a transition from K_{max}-invariant growth to ΔK-invariant growth at the load ratio at which $K_{min} = K_{cl}$. This transition is most apparent in (c) where the threshold envelope changes from nearly vertical to nearly horizontal. The continued downward slope of the threshold envelope at high K_{max} values is presumably independent of closure.

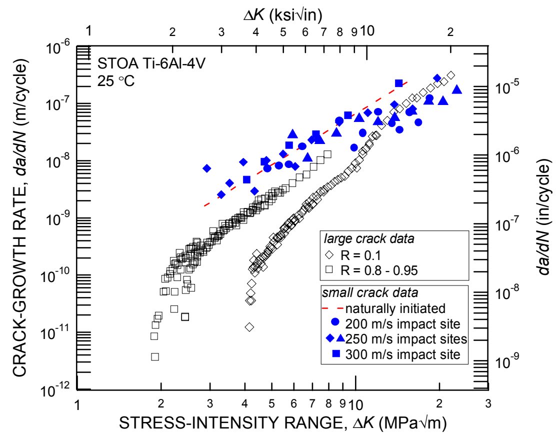


Figure 4. Comparison of worst-case large-crack propagation data to fatigue growth from naturally initiated small cracks and small cracks originating from sites of foreign object damage.

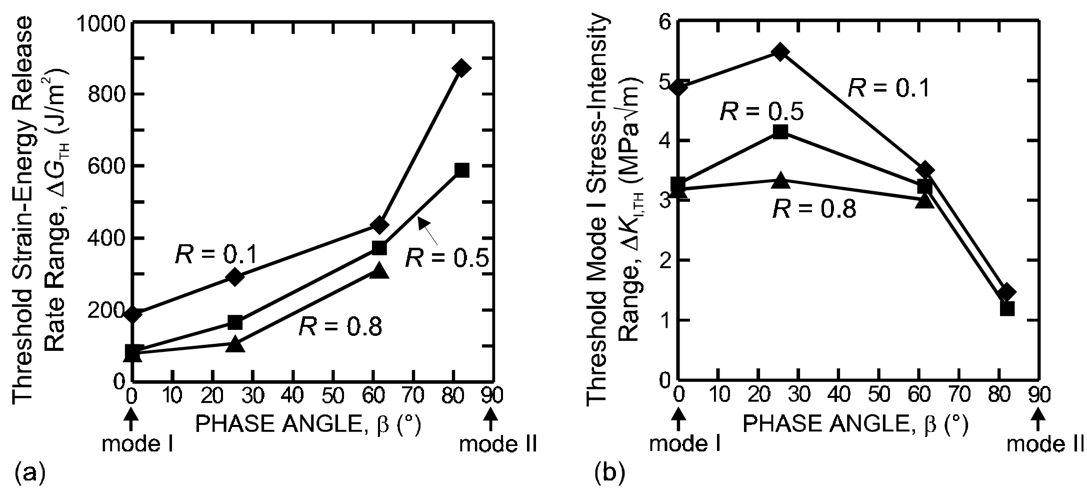
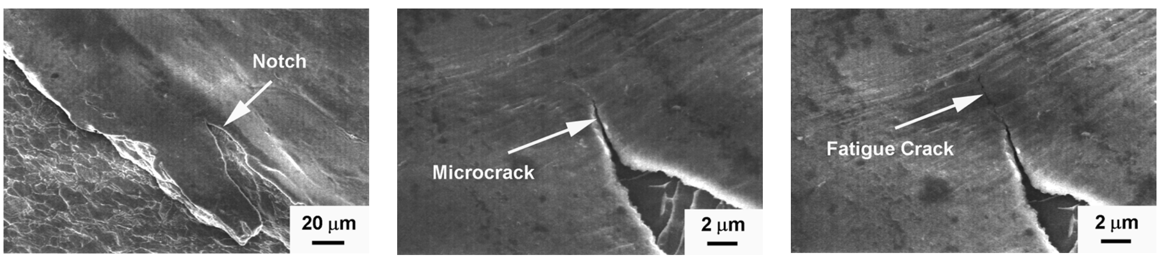


Figure 5. (a) Mixed-mode fatigue-crack growth thresholds in bimodal Ti-6Al-4V are plotted in terms of the range in strain-energy release rate at threshold, ΔG_{TH}, as a function of the applied phase angle, β, for load ratios of 0.1, 0.5, and 0.8. ΔG_{TH} is observed to increase with β. (b) For the same mixed-mode loading conditions, the mode I stress-intensity range at threshold, $\Delta K_{I,TH}$, is plotted as a function of β. $\Delta K_{I,TH}$ is observed to increase slightly as β increases from 0° to 26° and then decrease for β = 62° and 82° [11].

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 role of foreign-object damage (FOD) induced microcracks (~2 to 25 µm in surface length) (Fig. 6) on the earliest stages of FOD-induced high-cycle fatigue (HCF) failures in a Ti-6Al-4V alloy, $\alpha+\beta$ 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 3.2 mm steel spheres on the flat surface of fatigue test specimens to simulate FOD, it was found that the resistance to HCF is markedly reduced due to earlier crack initiation [12]. Premature crack initiation and subsequent near-threshold crack growth were primarily affected by the stress concentration associated with the FOD indentation and the presence of small microcracks in the damaged zone (seen only at the higher impact velocities) [13]. Moreover, the effect of residual stresses and microstructural damage from FOD-induced plastic deformation at the indent sites were assessed in terms of fatigue strength degradation. It is shown in Figure 7 that FOD-initiated cracks that are of a size comparable with microstructural dimensions, can propagate at applied stress-intensity ranges on the order of $\Delta K \sim 1$ MPa√m, i.e., a factor of roughly two less than the "worst-case" threshold stress-intensity range in Ti-6Al-4V [10] for a crack of a size large compared to microstructural dimensions (a "continuum-sized" crack). Correspondingly, for FOD-initiated failures, where the critical condition for HCF must be defined in the presence of microstructurally-small cracks, the threshold against crack growth from FOD-induced microstructurally-small cracks can be defined, in terms of *stress concentration corrected* stress ranges, from the "El Haddad" line ($\Delta K = Y\Delta\sigma\sqrt{[\pi(2c + 2c_o)]}$ [14]) in the Kitagawa-Takahashi diagram [15] (Fig. 8), provided the limiting conditions are described in terms of the 10^7-cycle (smooth-bar) fatigue limit (at microstructurally-small crack sizes) and worst-case large-crack fatigue threshold (at larger, "continuum-sized" crack sizes).



a) b) c)

Figure 6. Scanning electron micrographs showing the presence of microcracking at crater rim of a FOD indent after the highest velocity (300 m/s) impacts. Micrographs show (a) local notches at crater rim caused by plastic flow of material, (b) microcracks emanating from such notches, and c) subsequent fatigue-crack growth initiated at such microcracks after 5000 cycles at σ_{max} = 500 MPa (R = 0.1).

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

The fatigue-crack propagation behavior of a nickel-base superalloy has been evaluated at ambient and elevated temperatures over a range of frequencies and load ratios. Interesting effects of microstructure and frequency on the fatigue thresholds, not predicted from the literature, are being explored in detail. Current efforts focus on quantitative fractography and TEM studies of deformation microstructures, which in conjunction with each other will lead to a better understanding of the unusual threshold behavior.

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. [16]. 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.

Effects of temperature: Fatigue-crack growth curves for both structures at room temperature, 550°C and 650°C under identical conditions (R = 0.7, ν = 1000 Hz) are shown in Fig. 9. It is evident that crack-growth rates increase significantly as temperature is increased. Table I lists the average ΔK_{th} threshold values under the selected experimental conditions. Threshold values

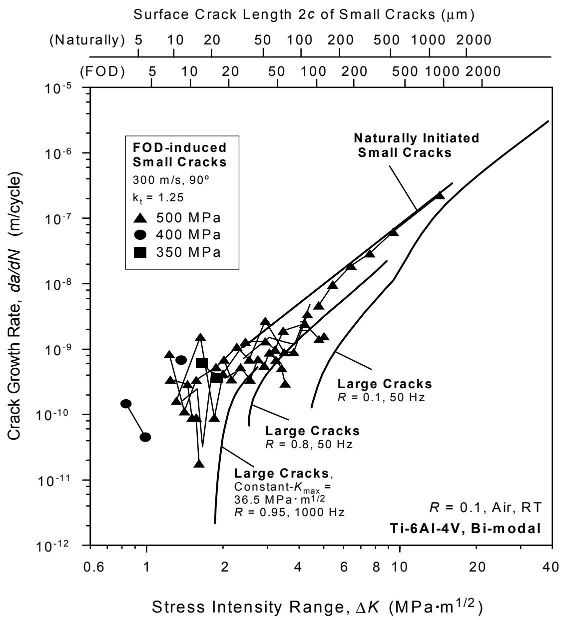


Figure 7. Crack-growth rates as a function of applied stress-intensity range of FOD- and naturally-initiated small cracks and through-thickness large cracks in bimodal Ti-6Al-4V. Small-cracks were initiated at σ_{max} = 650 MPa (R = -1) [8]. Large-crack growth data for $R \leq 0.8$ were derived from constant load-ratio tests, whereas for $R \geq 0.8$, constant-K_{max}/ increasing-K_{min} testing was used [10].

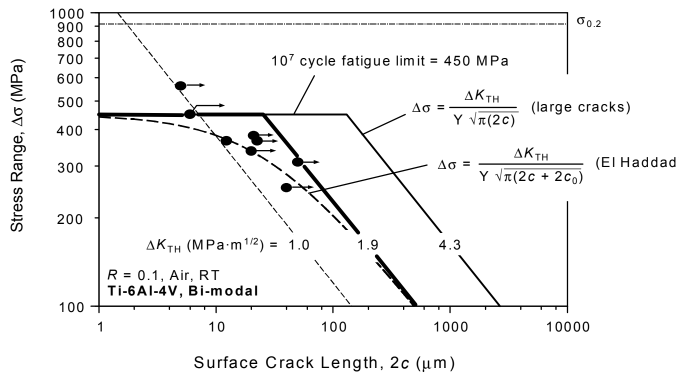


Figure 8. Modified Kitagawa-Takahashi diagram representing the threshold crack-growth conditions ($da/dN = 10^{-11}$-10^{-10} m/cycle) for FOD-induced small-cracks in Ti-6Al-4V. Plotted is the threshold stress range as a function of surface crack length. Data points are corrected for the stress concentration of the FOD indents.

were verified at least once, and in every test measurements were considered accurate to within ± 0.1 MPa√m of the reported mean values. It is evident from these data that ΔK_{th} thresholds decrease significantly between room temperature and 650°C. An exception to the decrease in thresholds with increasing temperature was seen between 550° and 650°C for the fine-grain material at 100 Hz, where threshold values were increased by < 10%. However, similar to the reported literature on superalloys, as the temperature is increased from 25° to 650°C, ΔK_{th} fatigue thresholds were lowered by about a factor of two.

Effects of frequency: In earlier work [16], no effect of frequency between 50 and 1000 Hz was found at room temperature. However, as KM4 is strain rate sensitive at higher temperatures, an increase in fatigue-crack growth rates at lower frequencies was seen in both microstructures at 650°C. At 550°C in the coarse-grained structure, crack-propagation curves were statistically indistinguishable at frequencies of 100 and 1000 Hz. Inspection of Table I shows that thresholds are a complex function of frequency and microstructure. At 650°C, thresholds are higher at 1000 Hz (compared to 100 Hz) for the coarse-grain material (by 10-25% depending on R), while they are lower at 1000 Hz (compared to 100 Hz) for the fine-grain material (again by 10-25%). At 550°C, the trends are reversed. The fine-grain material has a higher threshold at higher frequency (the opposite of that observed at 650°C), while thresholds are relatively insensitive to frequency for the coarse-grain material at 550°C. Such complex trends are currently under investigation.

Effects of microstructure: The effect of microstructure on near-threshold fatigue behavior in KM4 at room temperature is reported in ref. [16]. In general, the coarse-grained material displays superior properties, with higher ΔK_{th} thresholds. An exception to this was seen at 650°C (100 Hz) where the fine-grained microstructure had the higher fatigue threshold value. This result is under investigation.

Table I: ΔK_{th} threshold values under the selected experimental conditions. All values in MPa√m.

Temperature	Fine grain material				Coarse grain material			
	100 Hz		1000 Hz		100 Hz		1000 Hz	
	R=0.4	R=0.7	R=0.4	R=0.7	R=0.4	R=0.7	R=0.4	R=0.7
25°C	-	-	8.4	6.8	-	-	10.3	9.9
550°C	5.1	4.4	5.9	5.0	6.15	5.6	6.15	5.35
650°C	5.2	4.65	4.25	3.9	4.55	4.0	5.6	4.6

Effects of load ratio: An increase in load ratio resulted in higher growth rates in both microstructures; this was found to be a result of an increase in the effective stress-intensity factor from diminished crack closure at higher R. In general, load ratio effects were more pronounced in the near-threshold crack growth regime, again consistent with the role of crack closure.

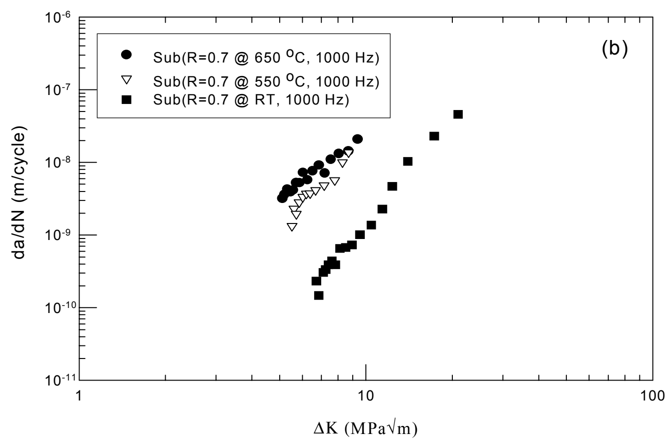


Figure 9. Fatigue-crack propagation curves for fine-grained (Sub in legends) KM4 at three different temperatures of ambient, 550° and 650°C.

Modeling and Experimental Studies on Fretting Fatigue (MIT)

Through a combination of analytical modeling, numerical simulations and controlled experimentation, the overall objective of this project is 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 for 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 considered analytically using the crack analogue methodology [17], while the spherical contacts were modeled using finite elements [18] and investigated experimentally [19,20] and modeled analytically [21].

In the past year our objectives were to (a) study the effect of roundness of a nominally sharp contact geometry on fretting fatigue crack initiation [22]; (b) systematically characterize the influence of contact and bulk stresses, contact geometry, and material microstructure on the fretting fatigue behavior of Ti-6Al-4V [23,24]; (c) develop quantitative analytical and experimental tools for evaluating the effectiveness of different palliatives such as shot-peening, laser shock-peening or coatings, for fretting fatigue [25,26]; (d) develop a new framework for understanding the fundamentals of foreign object damage within the context of dynamic indentation [27].

"Notch Analogue" model for fretting fatigue [22]: The effect of roundness of a nominally sharp contact geometry on fretting fatigue crack initiation has been 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 [23,24]: A systematic investigation of the fretting fatigue behavior of the Ti-6Al-4V alloy in both the mill annealed and bimodal 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 the acicular, Widmanstätten, and martensitic Ti-6Al-4V as well. Important results from this study were: (a) 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 (Fig. 10); (b) 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 (Fig. 11); (c) 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 (Fig. 12); (d) with the exception of the martensitic structure which displayed enhanced fretting fatigue resistance, the other microstructures did not exhibit a significant improvement in fretting fatigue resistance, compared to the basic STOA or the mill annealed microstructure; (e) 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; (f) 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.

Palliatives for fretting fatigue [25,26]: Possible palliatives of fretting fatigue include surface modification and generation of compressive residual stresses through treatments such as shot-peening, laser shock-peening or coatings. Our work has focussed on two key areas: (a) assessing the influence of compressive residual stresses and surface topology on the fretting fatigue crack initiation and propagation, and (b) developing a convenient and quantitative indentation technique for the determination of residual stresses as a function of depth. In this ongoing study, optimal surface conditions needed for accurate and quantitative measurement of residual stresses are identified. By comparing the force and depth of penetration relations obtained for shot-peened and stress-free surfaces, the sign and magnitude of the residual stresses are determined and compared to the residual stress measurement obtained from X-ray measurements.

Dynamic indentation [27]: A new framework has been developed within the context of dynamic sharp indentation, in order to develop a fundamental understanding of the foreign object damage phenomenon, where a sharp faceted particle traveling at a high relative velocity strikes an aircraft structure or an engine blade causing substantial material damage. A one-dimensional, analytical model for dynamic sharp indentation (based on Kick's law, i.e., the indentation load varies with depth in a parabolic manner), was developed to predict critical parameters such as the peak and residual indentation depths, contact time, and rebound velocity as functions of impact velocity, indenter mass and target properties. The model predictions were validated with finite element results. For materials that displayed rate-dependent plasticity, deviations from the classic Kick's law for indentation were noted. Furthermore, the dynamic indentation of spherical particles was also examined.

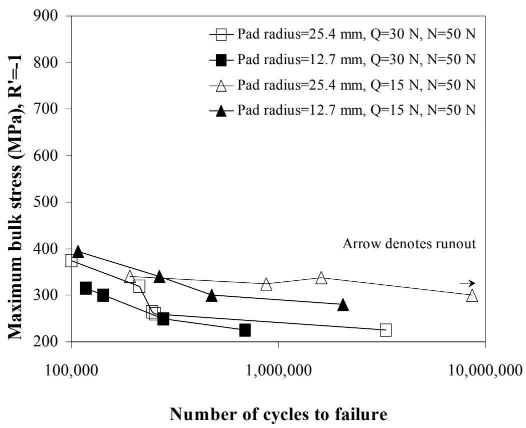


Figure 10. Fretting fatigue results from experiments on the mill-annealed Ti-6Al-4V illustrating variation of total life with changes in the bulk stress applied to the specimen, for a variety of contact geometry and loading conditions.

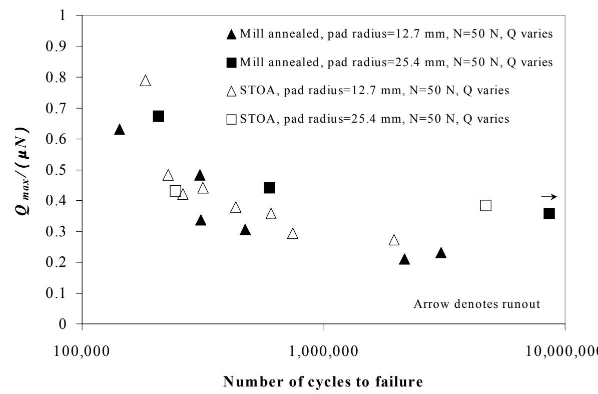


Figure 11. Fretting fatigue results from experiments on the mill-annealed and STOA Ti-6Al-4V illustrating variation of total life with changes in the tangential loads applied to fretting contact (σ_b = 300 MPa, μ=0.95).

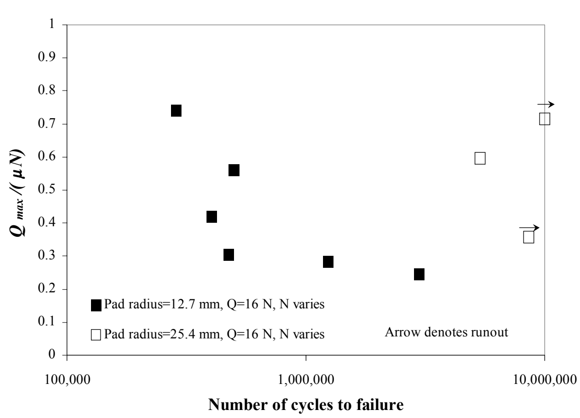


Figure 12. Fretting fatigue results from experiments on mill-annealed Ti-6Al-4V illustrating variation of total life with changes in the normal loads applied to the fretting contact, for a variety of contact geometry (σ_b = 300 MPa, μ=0.95).

Theoretical Studies of Fatigue, Foreign Object Damage and Fretting (Harvard)

During the past year, research has been completed on aspects of small crack growth in surface grains of polycrystalline metal alloys (Tvergaard, Wei and Hutchinson [28]) and research on foreign object damage (FOD) and its influence on fatigue cracking has continued.

Foreign object damage: The FOD work has been closely coordinated with experimental and theoretical activities conducted at Berkeley. The work over the past year extended our earlier research (Chen and Hutchinson [29]) to fatigue cracking at the bottom and rim locations of the FOD indent. Predictions for the critical size of the indent for which appreciable reduction in fatigue life is expected have been made, and estimates of the initial crack size associated with threshold fatigue cracking have been made as a function of the indent size. The work has also been extended to deep indents, characteristic of the highest velocities (300m/s) of particle impact used in the Berkeley experiments.

Results for a deep indent with emphasis on the roles of both residual stress and alteration of stress due to the geometry of the indent are shown in Figs. 13 and 14. Fig. 13 gives plots of the computed elastic stress concentration factor due to the indent at the bottom of the indent (point A) and at the rim (point B). These are due to the geometry change induced by the indent. Fig. 14 shows two sets of curves of critical threshold crack size versus $\kappa_{applied}$. The member of each set corresponds to a level of indentation shown. Here, $\kappa_{applied}$ denotes the ratio of minimum to maximum stress associated with the cyclic loading history applied to the specimen. The dashed set of curves neglects the influence of the residual stress but accounts for the geometric stress concentration. The solid set of curves accounts for both residual stress and the geometric effect. It is clear that the residual stress has a pronounced effect when $R_{applied}$ is low.

Motivated by issues that have arisen in attempting to reconcile theory and experiment in the FOD experiments, dynamic finite element simulations for normal impact of a specimen by a rigid spherical FOD particle have been performed. In particular, the effect of the finite size of the specimen has been studied. Accounting for the size of the test specimen is important in helping to resolve the discrepancies because the Berkeley specimens are not very large compared to the indent size. The objective has been to compute the stress and strain at the bottom of the indent so that these results can be compared with the Berkeley strain measurements. The calculations account for inertial effects but do not include material strain rate sensitivity. (Calculations which include strain rate sensitivity have been performed, but material data at the highest rates experienced in the impact are not available. This aspect of the research ongoing.) The results obtained thus far show that accounting for the dynamic effect on the impact brings the elastic strain at the bottom of the indent closer to the values measured by the Berkeley group, but there are discrepancies which are still not accounted for.

Mixed-mode small-crack K solutions: Work has also been reported on the problem of semi-circular and semi-elliptical surface cracks subject to arbitrary loading, i.e. to mixed-mode loading conditions. The study is motivated by concerns that mixed-mode loadings may adversely affect threshold conditions for fatigue cracks. The aim of the work is to provide a compendium of useful elastic crack solutions for the full range of possible loads, thereby extending the well known results of Newman and Raju to mixed-mode conditions. This work was performed in response to suggestions from the larger group of MURI researchers that it was very important to assess whether mixed-mode surface cracks might be more critical than mode I cracks under threshold initiation. The study provides strong evidence that it is unlikely that this will be the case, although the final conclusion will have to await some definitive experiments.

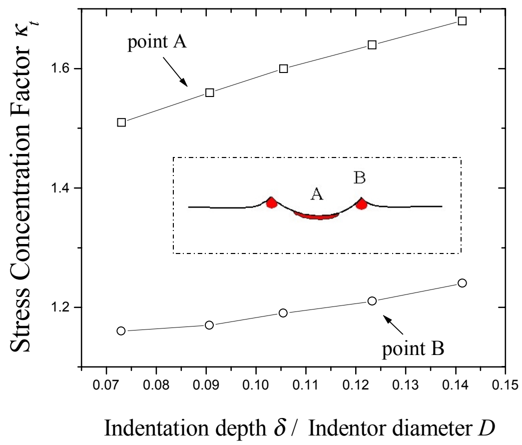


Figure 13:. Elastic stress concentration factors at the bottom and rim of deep indents.

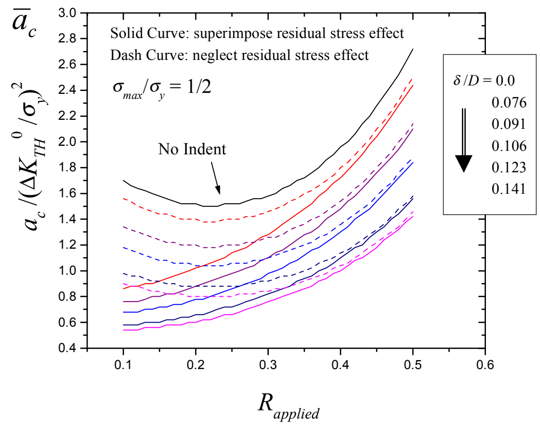


Figure 14: Interactions between the residual stress and stress concentration factor for semi-circular cracks at the rim. The effect of residual stress is significant at low applied load ratios *R*.

Residual Stress Measurements around Sites of Simulated Foreign Object Damage (UCB)

The objective of this study is to develop and apply an experimental characterization tool capable of documenting the magnitude of the residual stress field left by a FOD impact, and to verify such measurements through numerical (FEM) studies of such damage sites at Harvard.

While the application of the x-ray diffraction technique to the determination of residual stress fields has been well documented for several decades, the problem of a FOD impact provides several unique complications preventing the use of traditional techniques. These complications are (a) the need for a small spot size (~300 μm or less) to correctly sample the strain *gradient* over millimeter dimensions and (b) the need for a highly-parallel x-ray source to prevent divergence errors while sampling a non-planar surface (i.e. the indent ridge and concave floor). These two complications together prevent the use of lab-based sources. Therefore, a synchrotron based technique has been developed where the significant intensity increase (several orders of magnitude over conventional lab sources) available at the synchrotron allows these conditions to be met while affording rapid data collection. The experiments are identical to conventional x-ray diffraction techniques, with the exception of the highly parallel intense source, and the use of collimating optics (typically a Si_{111} analyzing crystal). Symmetric diffraction and the $\sin^2\psi$ technique have been used to measure surface normal and in-plane strains respectively at various positions around sites of simulated foreign object damage. The damage was simulated in Ti-6Al-4V by impacting a nominally stress-free surface with spherical indenters at velocities of 300 m/s, 200 m/s, and 0 m/s (quasi-static). Specific results are listed below.

- The surface-normal residual strain field has been determined experimentally by symmetric powder diffraction and numerically by FEM. There is good agreement between these two results when the impact was formed at moderate velocities (200 m/s) (Fig. 15). However, when the impact was formed at high velocities (300 m/s), there is a notable discrepancy between the FEM results and the x-ray results, the latter showing a less intense residual strain field. These discrepancies are attributed to the quasi-static nature of the first-cut FEM simulation, and subsequent reanalysis, taking into account time-dependent effects, shows the discrepancy between the FEM and x-ray methods to diminish.
- Each impact velocity produces very different levels of residual stress at the surface of the base of the crater. The equibiaxial stresses measured at the base of the crater are approximately -1000, -500, and +50 MPa at 0, 200, and 300 m/s respectively. Interestingly, in the 300 m/s case which has the highest tensile stresses of the three cases, fatigue cracks do not tend to form at the crater floor, but instead, form at the crater rim due to the formation of incipient microcracks at the rim during the impacting process.

- The relaxation of residual stresses due to subsequent fatigue cycling ($\sigma_{max,\ nominal}$ = 500 MPa, R = 0.1) after impact has been experimentally observed. This relaxation, however, is only observed when (a) the magnitude of the residual stresses are sufficiently high, and (b) the residual stresses are sufficiently close to the crater to promote stress-amplitude magnification via the stress-concentration factor of the indent. Moreover, there is an indication that more relaxation occurs at the crater floor than at the rim of the crater.
- There is a high degree of point-to-point variability in the observed residual strain field. A fully annealed sample with no macroscopic residual stresses, can exhibit ~500 με (~50 MPa equivalent uniaxial stress) of variability depending on the location of the spot when interrogated with a 500µm x 500 µm spot size. This observed variablity is sufficiently above the reproducible resolution of the technique, which is ~100 µm (10 MPa equivalent uniaxial stress). Most likely this variability is associated with local residual stresses (so-called "microstresses") locked in during the formation and cool-down of the anisotropic microstructure. An example of a crater survey, Fig. 16, shows the high degree of variability, causing local "hot spots" of strain (the red peaks).

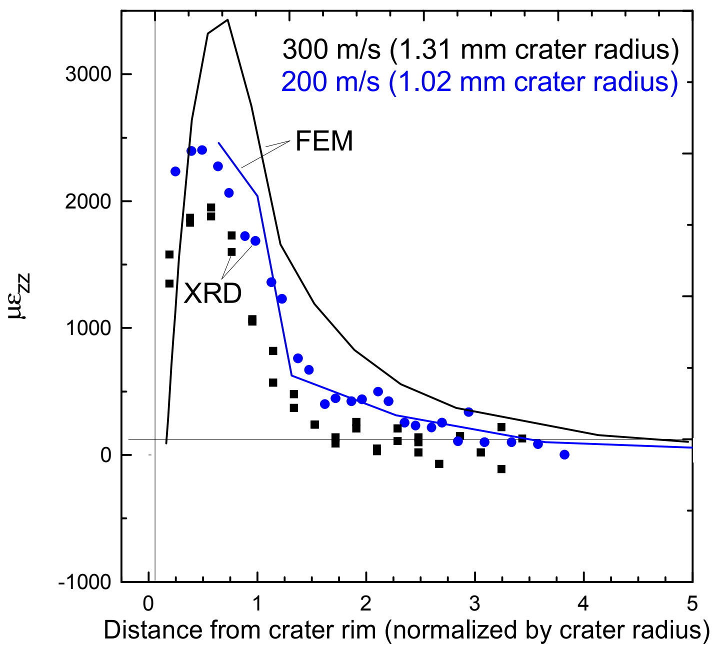


Figure 15. Survey of residual strain gradient emanating away from the crater rim at the surface of the specimen. The FEM results (lines) compare well to x-ray diffraction experiments (points) at 200 m/s but there is significant discrepancy at 300 m/s.

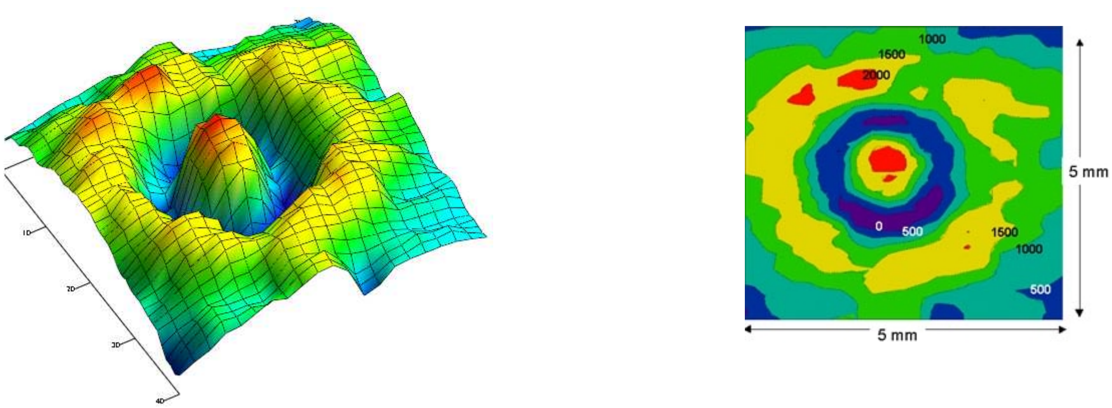


Figure 16. Two views of a 2-dimensional surface-normal strain survey around a site of damage formed from a 200 m/s impact. The isostrain contour values in the right image are in units of µε. Red peaks are associated with high local strain.

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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, has been elected Fellow of TMS, Fellow Class of 2000.
S. Suresh, was offered Clark Millikan Endowed Chair at Cal. Tech.- sabbatical leave 1999-2000.
B. L. Boyce, was awarded a Hertz Foundation Fellowship for research at Berkeley.
P. Birch, was awarded a NSF Graduate Fellowship for research at MIT.

Transitions

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