AFRL-ML-WP-TP-2006-500

LIFE PREDICTION OF FRETTING FATIGUE WITH ADVANCED SURFACE TREATMENTS (PREPRINT)

Patrick J. Golden and Michael J. Shepard

MAY 2006

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MATERIALS AND MANUFACTURING DIRECTORATE
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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE ***(DD-MM-YY)***	**2. REPORT TYPE**	**3. DATES COVERED** ***(From - To)***
May 2006	Journal Article Preprint	

4. TITLE AND SUBTITLE
LIFE PREDICTION OF FRETTING FATIGUE WITH ADVANCED SURFACE TREATMENTS (PREPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
N/A

6. AUTHOR(S)
Patrick J. Golden and Michael J. Shepard

5d. PROJECT NUMBER
M02R

5e. TASK NUMBER
30

5f. WORK UNIT NUMBER
00

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Metals Branch (AFRL/MLLMN)
Metals, Ceramics and NDE Division
Materials and Manufacturing Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7750

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-ML-WP-TP-2006-500

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Materials and Manufacturing Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7750

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL-ML-WP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-ML-WP-TP-2006-500

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Journal article submitted to Materials Science and Engineering A, published by Elsevier B.V.

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This paper contains color. PAO Case Number: AFRL/WS 06-1313, 16 May 2006.

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15. SUBJECT TERMS
Fretting, Ti-6Al-4V, DLC, Laser Shock Processing, Low Plasticity Burnishing, Life Prediction

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Patrick Golden
Unclassified	Unclassified	Unclassified	SAR	30	**19b. TELEPHONE NUMBER** *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Life Prediction of Fretting Fatigue with Advanced Surface Treatments

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Abstract

Laboratory fretting results with diamond like carbon coating, low plasticity burnishing, and laser shock processing as well as with no surface treatments are presented. A method of life prediction for a dovetail type specimen is demonstrated with the laboratory results. In general, the life prediction calculations agree with the laboratory results when the appropriate coefficient of friction and compressive residual stresses are accounted for in the analysis. Some of the assumptions made in the analysis are qualitatively confirmed with experimental observations.

Keywords

Fretting, Ti-6Al-4V, DLC, Laser Shock Processing, Low Plasticity Burnishing, Life Prediction

1. Introduction

Fretting occurs when two components are pressed together with a normal force and are subjected to oscillating friction forces [1,2]. This results in a small, relative, oscillating tangential displacement and often very high cyclic stresses leading to fatigue damage. Fretting can be described by two modes. The first is gross slip, wherein the entire contact interface has a relative displacement or slip during part of the load cycle. The second mode is partial slip, which occurs when the contact interface is "stuck" together, however, slip zones typically exist

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at the edges of the contact interface. Fretting is a problem in many aerospace applications and has been identified as one of the costliest sources of in-service damage related to high cycle fatigue (HCF) in the US Air Force [3]. In a turbine engine, the attachments between the rotating blade and disk often experience mixed-mode fretting with portions of the load history resulting in either partial slip or gross slip fretting depending on the magnitude of the excursions in engine speed and temperature.

In order to avoid component redesign to decrease problems due to fretting, various palliatives are available. Coatings and lubricants are used to reduce damage due to wear and reduce the peak stresses in the contact interface. These work by both reducing the coefficient of friction, μ, and by providing an interfacial layer to reduce wear on the base material. In a dovetail or fir tree type blade to disk attachment, a reduced μ can decrease the shear load and thus reduce the crack driving force. Analysis also shows that for the same shear load, a smaller μ will lower the peak stress that contributes to the initiation of cracks [4]. Soft coatings such as Cu-Ni-In along with solid lubricant MoS_2 [5] provide the desired effect; however, these coatings can wear out over time. Several researchers have investigated the use of thin, hard, low-friction coatings such as diamond like carbon (DLC) or TiN [6,7]. These coatings offer a potential alternative to those currently in use. They are wear resistant and often maintain a low coefficient of friction. An additional practical advantage to these coatings is the non-line-of-sight application techniques available such as plasma immersion ion processing method or radiofrequency plasma deposition [8], which allow application to hidden surfaces such as small dovetail slots in engine disks.

Research has also shown that shot peening [9,10] and other advanced surface treatments such as laser shock processing and low plasticity burnishing [11,12] that induce compressive residual stresses are beneficial and can extend fretting fatigue life in laboratory experiments. The term advanced surface treatments is used here to describe any of several methods of inducing deep compressive residual stress into the material with relatively low cold work. The compressive residual stresses due to these surface treatments reduce the local stresses that initiate cracks and drive crack coalescence and growth.

The objective of this paper is to demonstrate a method of life prediction applied to fretting tests. Laboratory specimens have been treated with several palliatives including a DLC coating, LSP, LPB, and the combination of LSP or LPB with DLC. These different palliatives work to increase fretting life through different means. Low friction coatings may reduce peak stresses and surface damage which lead to crack nucleation, while surface treatments that induce compressive residual stresses may slow or stop crack growth. Techniques to account for these coatings and surface treatments will be discussed and demonstrated.

2. Experiments

The material used in this study was a Ti-6Al-4V alloy prepared for the US Air Force National High Cycle Fatigue program. The material was an $\alpha + \beta$ forged alloy. After being forged the material was solution treated and overaged (STOA) at 932°C for 75 minutes, fan cooled, and then mill annealed at 704°C for two hours. This heat treatment resulted in approximately 60% primary α and 40% transformed β microstructure. Both the fretting pads and specimens were machined from this material.

The test setup is shown in Figure 1. This fixture has been described in previous work by Golden and Nicholas [13]. As shown in the photograph, the pads are placed into slots in the fixture and screwed in place through the fixture into tapped holes on the bottom of the pads (not visible in photograph). The two fretting pads are replaced after each test. The geometry of the fretting pads was two-dimensional and can be described as a rounded flat profile. The flat region is 3 mm in length and the edges of the flat are 3 mm in radii for 11° then tapered to the edges. The width of the pads and specimens is 7.6 mm. This contact profile was chosen because it is representative of actual contact profiles found in the attachment between fan or compressor blades and disks in US Air Force turbine engines.

Of particular importance to the subject of this paper was the quantification of the forces at the contact interface between the specimen and pad. The contact loads were necessary inputs to the stress analysis which fed the life prediction analysis. In this test setup it was only possible to directly measure the remotely applied cyclic force, F_{app}, using a load cell. The normal and shear contact forces, P and Q respectively, as well as the contact moment, M, could not be measured directly. To circumvent this problem, additional strain gage instrumentation was added to the fixture that, with corresponding finite element method (FEM) analysis, resulted in calculation of the contact loads, P and Q. Additional modeling has shown that the expected moment was nearly zero for these experiments and the moment was, therefore, ignored in the analysis.

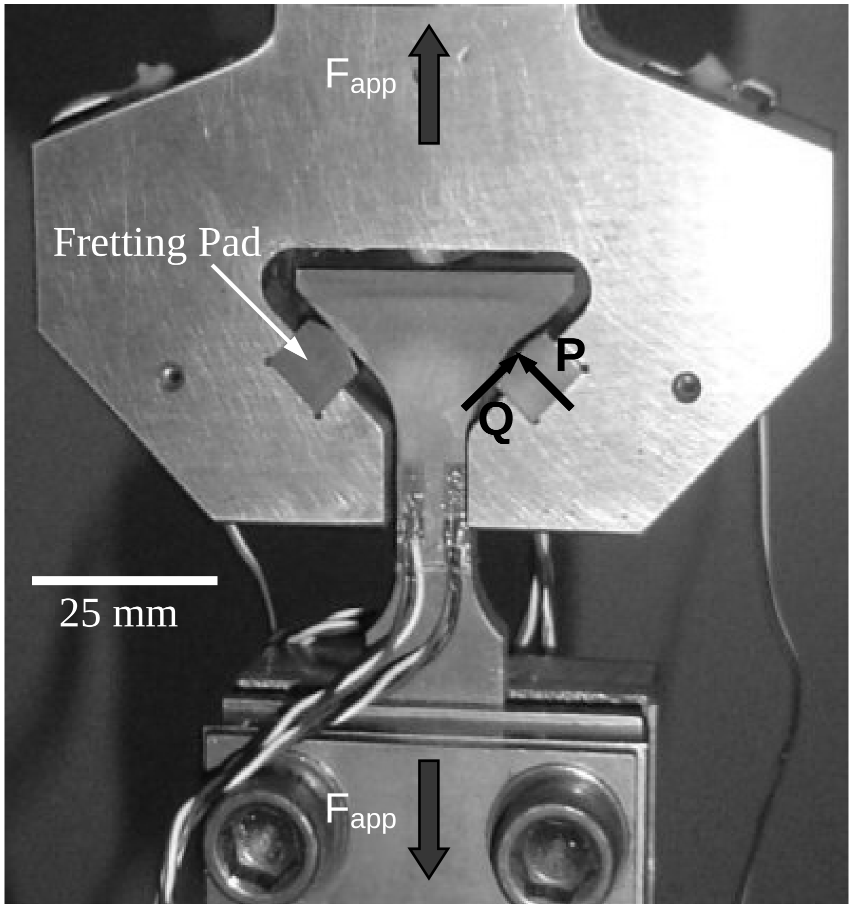

Figure 1: Photograph of the dovetail fretting fatigue fixture used in this study.

Several coatings were considered as part of the experimental study. The coatings were only applied to the specimen contact surfaces and not the fretting pads. The chosen coatings included DLC, Ni-B, Molybdenum, and Nitride. These 4 coatings, their application to the titanium specimens, and the corresponding fretting fatigue test results are described in detail in Golden et al. [14]. The test results of the DLC coated specimens showed an order of magnitude increase in life and approximately 30% increase in fretting fatigue strength at 5 million cycles. The test results from the other 3 coatings were either poor compared to no coating, as with the nitride, or they were indistinguishable from results from specimens with no coatings, as with the Ni-B and Molybdenum. The DLC coated specimens were considered for stress and life analysis.

Two different advanced surface treatments were also applied to a number of specimens in order to induce compressive residual stresses near the surface in the contact region. Twelve specimens were processed in the contact region, half with laser shock processing (LSP) and half with low plasticity burnishing (LPB). Half of the specimens with each treatment were tested without coatings to determine the effect of just the residual stress on the life. The other six specimens were coated with DLC to evaluate the combined effect of the compressive residual stresses and low friction coating. The residual stresses in the treated areas of the specimens were measured into the depth. Measurements were made using X-ray diffraction techniques in the slip direction adjacent to the fretting scars. Material removal was performed by electropolishing thin layers between X-ray diffraction measurements. The final residual stress profile was reported after corrections were made for stress gradient and material removal [15,16]. The results can be seen in Figure 2. This residual stress profile was extrapolated to the approximately 10 mm thickness of the specimens. The tensile residual stress was included in the extrapolation so that the final distribution satisfied equilibrium.

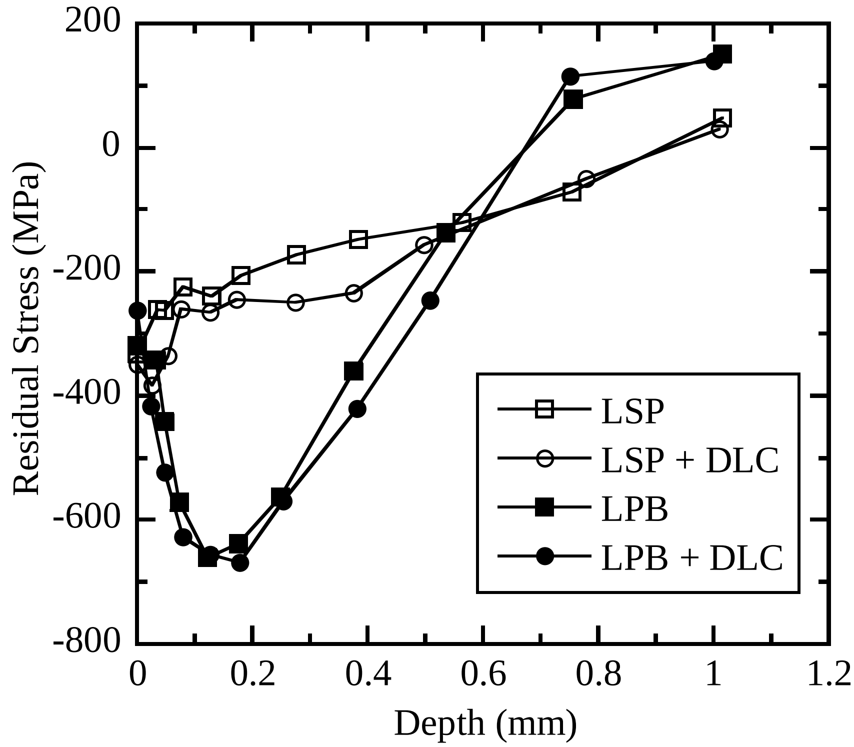

Figure 2: In-depth residual stress measurements taken from dovetail specimens just outside the fretting scar [13].

Test results from the experimental program are summarized in Table 1. The table includes the loads and test results necessary to model these experiments and evaluate fretting fatigue life prediction methods. All tests were conducted with a remote load ratio, R, of 0.1. Failure was defined by a large crack which was typically 5 mm or greater in length. Six different test conditions were evaluated. These included: bare (baseline), DLC coated, LSP treated, LPB treated, LSP with DLC, and LPB with DLC. Five of the twenty-six specimens tabulated have two or more rows associated with them. These tests were step loaded. After 2 million cycles, the remotely applied force was increased by 2.4 kN (approximately 10%) and the cyclic loading was repeated. This continued until failure or until the maximum safe cyclic load for the fixture was reached. Further details on the general step loading procedure can be found in Maxwell and Nicholas [17].

Table 1: Results from previous testing [14] that were used in the life prediction analysis.

Test ID	RS	Coat	F_{max} (kN)	P_{max} (kN)	Q_{max} (kN)	P_{min} (kN)	Q_{min} (kN)	Cycles
04-176	None	None	18.0	9.6	3.1	2.2	-0.9	1,371,301
04-182	None	None	18.0	9.8	2.8	2.5	-1.0	10,000,000
04-183	None	None	18.0	9.7	3.0	2.3	-1.0	693,000
04-179	None	None	20.0	11.1	3.0	2.6	-1.2	995,431
04-180	None	None	20.0	11.1	3.0	2.7	-1.3	919,896
03-800	None	None	22.0	11.9	3.6	2.4	-0.8	249,862
03-801	None	None	22.0	12.0	3.6	2.9	-1.2	346,221
04-181	None	None	22.0	12.2	3.3	2.9	-1.3	497,763
03-303	None	None	24.0	12.5	4.3	3.1	-1.2	163,958
03-795	None	DLC	24.0	13.2	3.7	2.9	-1.2	5,000,000
03-796	None	DLC	24.0	13.4	3.4	3.1	-1.4	2,902,329
03-797	None	DLC	24.0	12.2	4.7	2.9	-1.1	5,000,000
04-602	None	DLC	24.0	13.6	3.3	3.1	-1.4	5,000,000
04-605	None	DLC	24.0	12.4	4.6	3.1	-1.3	5,000,000
04-620	LSP	None	24.0	13.5	3.4	3.3	-1.5	7,150,940
04-622	LSP	None	26.4	14.9	3.7	3.5	-1.6	2,000,000
04-623	LSP	None	26.4	15.0	3.6	3.6	-1.8	1,295,741
04-625	LPB	None	24.0	13.9	3.1	3.5	-1.7	10,000,000
04-626	LPB	None	24.0	13.0	3.9	2.8	-1.1	2,000,000
			26.4	14.0	4.6	3.0	-0.9	2,000,000
			28.8	14.9	5.4	5.5	0.4	2,000,000
04-627	LPB	None	26.4	15.4	3.3	3.9	-2.0	2,000,000
			28.8	16.4	3.9	4.0	-1.9	350,511
03-802	LSP	DLC	26.4	15.0	3.5	3.5	-1.6	2,000,000
			28.8	15.4	4.8	3.1	-1.2	63,623
04-615	LSP	DLC	26.4	15.3	3.3	3.5	-1.6	2,000,000
04-616	LSP	DLC	26.4	15.5	3.1	3.6	-1.7	2,000,000
04-628	LPB	DLC	26.4	15.0	3.5	3.5	-1.6	2,000,000
			28.8	15.4	4.8	3.1	-1.2	2,000,000
04-630	LPB	DLC	26.4	15.3	3.6	3.4	-1.5	2,000,000
04-632	LPB	DLC	26.4	15.0	3.5	3.5	-1.6	2,000,000
			28.8	15.6	4.6	3.1	-1.1	2,000,000

3. Analytical Procedures

The objective of the analysis conducted in this paper was to exercise life prediction methods on a set of fretting fatigue data that has the normal and shear contact loads characterized and to a certain degree a characterization of the average and slip zone coefficients of friction. Variables in the testing that must be accounted for in the life prediction include the magnitude of the remote loading, presence of a coating, and presence of residual stresses. The stress analysis for this work was very similar to that used in Golden and Calcaterra [18] and was comprised of two main steps. The two steps included a quasi-analytical method of solving the singular integral equations (SIE) that define the contact problem, and a finite element method (FEM) model was applied to account for the geometry of the problem. The life prediction analysis included both crack nucleation and crack propagation. The material data needed to apply these models was generated using the same Ti-6Al-4V material during the US Air Force National High Cycle Fatigue program [19].

A schematic of a dovetail attachment is shown in Figure 3. On the left side of the schematic is a dovetail attachment with two materials being forced into contact with the resulting normal, P, and shear, Q, contact forces. The schematic describes a two-dimensional problem; in general, however, the problem is three-dimensional and includes an out of plane force as well as moments. The right side of the schematic shows the equivalent contact which has the same gap function, $h(x)$, which defines the problem. This equivalent contact was used in both the experiment and the analysis. The first step of the stress analysis was completed by calculating the contact tractions, $p(x)$ and $q(x)$ respectively, from the contact forces P, Q, and M. In these experiments it has been shown that the moment was negligible and it was ignored in the analysis. The tractions are calculated numerically by the SIE method described in Murthy et al. [20]. This version of the solution included the effects of the load history and the tractions at both the maximum and minimum load steps were obtained. An example of the tractions calculated for the profile used in these experiments is plotted in Figure 4. The pressure traction had peaks within the radius of the profile near each edge of contact. The shear traction also had peaks near the edge of contact. The shear traction was defined by $q = \mu p$ from the edges of contact to the peaks. This region is known as the slip zone. The remainder of the contact had zero slip and was the stick zone. The small anomalies in the shear traction inside the stick zone but near the slip zone were caused by the slip history from the load cycling from minimum to maximum.

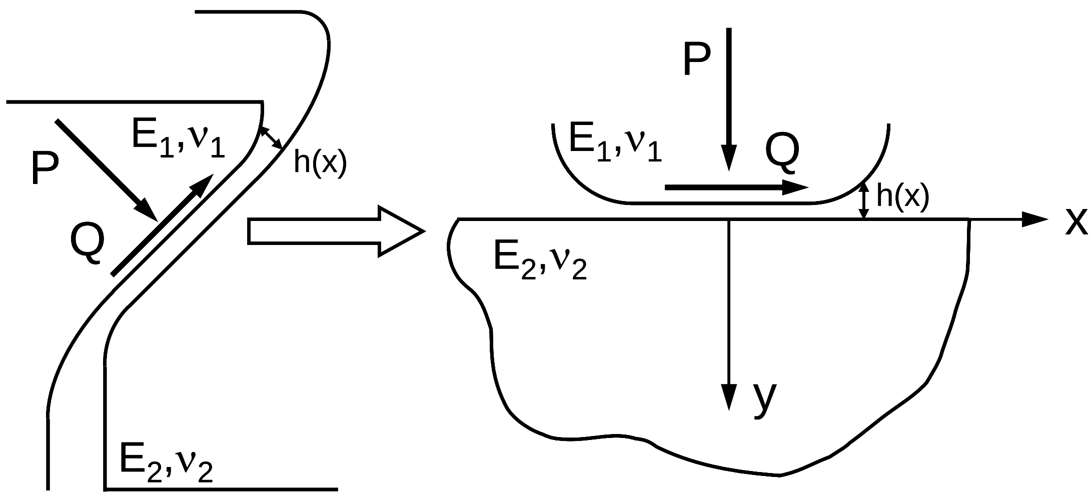

Figure 3: Schematic drawing of a dovetail contact and an equivalent contact geometry used in the experiment and the analysis.

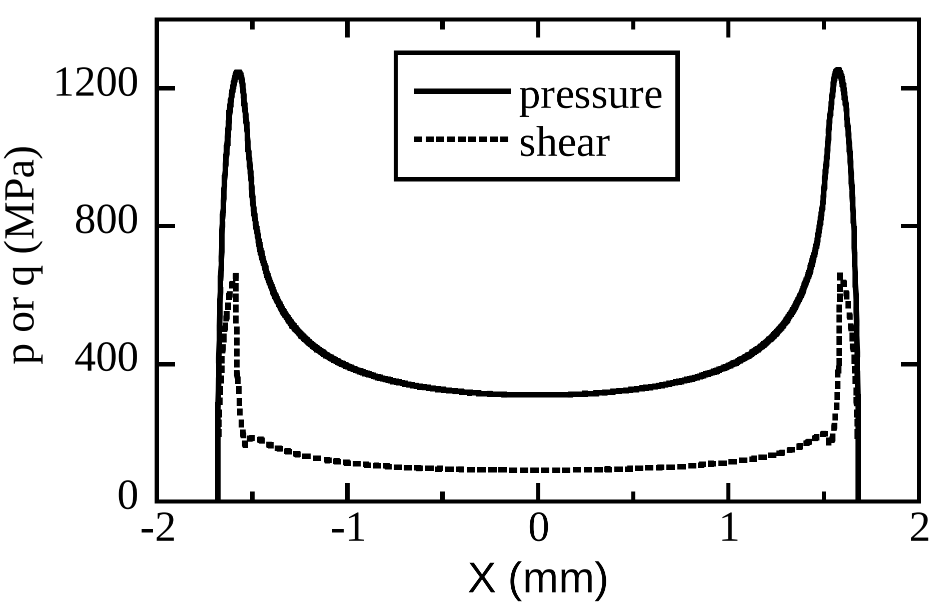

Figure 4: Typical pressure and shear tractions calculated using SIE method.

Once the tractions were known, the next step was to calculate the subsurface stresses. Two methods were available to accomplish this. First, a numerical solution [21] was available that solved for the subsurface stresses given the contact tractions and worked directly with the output of the SIE method. The advantage of this software was speed and accuracy. The disadvantage was that the subsurface stress solution assumes a semi-infinite half space for the boundary conditions on which the tractions were applied. The real problem was a dovetail shaped member with different boundary conditions so this solution alone was not sufficient. The second method was FEM. The advantage of FEM was that the correct boundary conditions were established in the model. Also, if the contact loads are unknown, as is typically the case in a real component, a full contact model can be performed to calculate the contact forces as well. In this work, the contact forces were already known so a simple model of the specimen was analyzed with the tractions calculated by the SIE method applied directly to the model. The disadvantage of this method was the accuracy near the edge of contact. A very high element density was required to achieve convergence in the stress analysis. The approach was to take advantage of both techniques and combine the subsurface results. Figure 5 is a plot of the tangential component of stress in the crack opening direction at the edge of contact. The results labeled ANSYS were from the FEM package and the results labeled SUBSURF were from the numerical solution of the same name used to calculate these stresses. The bulk stress was calculated by finding the difference in these solutions, however, the results near the surface were ignored due to the poor accuracy of the FEM solution. The bulk stress was then extrapolated back to the surface. The bulk stress represents the influence of the geometry on the contact stress gradient.

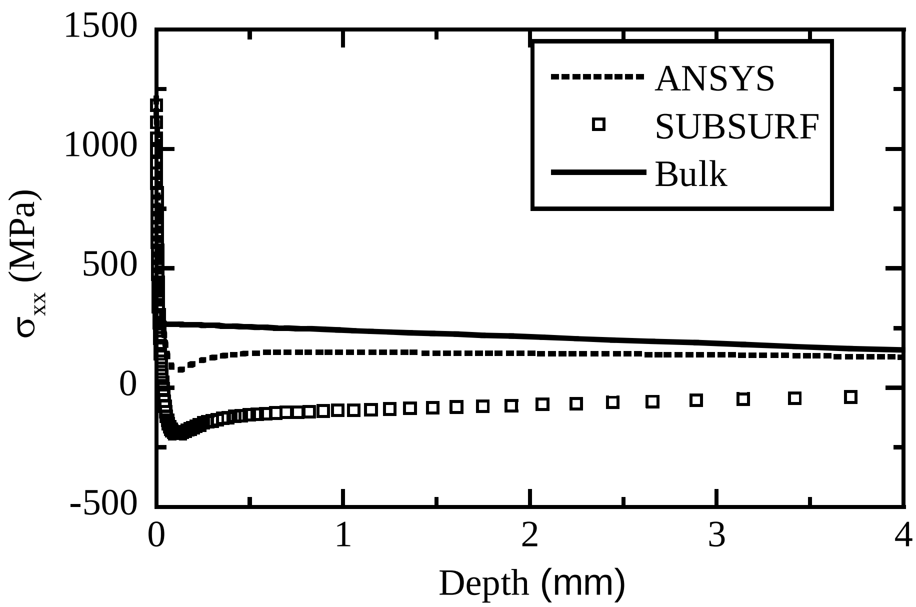

Figure 5: Plot of the tangential stress at the edge of contact as calculated by FEM and through numerical solution. The bulk stress is simply the difference between these two solutions.

Now that the stresses have been calculated, standard life prediction tools can be applied. The crack nucleation analysis used was an equivalent stress, σ_{eq}, calculation described in detail elsewhere [18,22]. Calculations of σ_{eq} accounted for the multiaxial stress state and mean stress and used only the surface stresses. The stress-life curve that fits σ_{eq} to life used uniaxial tests at multiple stress ratios, as well as biaxial tests, torsion tests, and notched tests with the same material used in this study. The crack propagation analysis used a fracture mechanics approach that also accounted for the local load ratio in the stress intensity factor range and used a sigmoidal crack growth law that accounts for crack growth threshold and fracture. The calculation of the stress intensity factor and the crack growth law used are discussed in detail in Golden and Grandt [23]. The stress intensity factor was calculated from the stress gradient into the depth of the material at the edge of contact along the actual crack path. The cracks typically grew along a path 15-20° from the normal to the surface away from the contact region. A generalized weight function procedure [23,24] was used to handle the very sharp stress gradient when calculating the stress intensity factors. The initial crack was assumed to be a semi-elliptical surface crack with a depth, *a*, of 25 μm and a surface length, 2*c*, of 250 μm. This crack size and shape was consistent with previous observations.

4. Results and Discussion

The results of the fretting fatigue tests with and without coatings and residual stress surface treatments were shown in Table 1. Additional results, although not the subject of this paper, were obtained with several other coatings at the same remote cyclic load as with the DLC coating. These coatings included a Nitride surface treatment, a flame sprayed Molybdenum coating, and Ni-B. The significance of these tests to the current work is the correlation between life and average coefficient of friction plotted in Figure 6. The nitride samples have a higher average coefficient of friction and a significantly reduced life. The Mo and Ni-B samples exhibit an initial average coefficient of friction similar to the baseline (no coating) tests and likewise a very similar life. Finally, the DLC coated specimens have a reduced coefficient of friction and a life extension of over an order of magnitude.

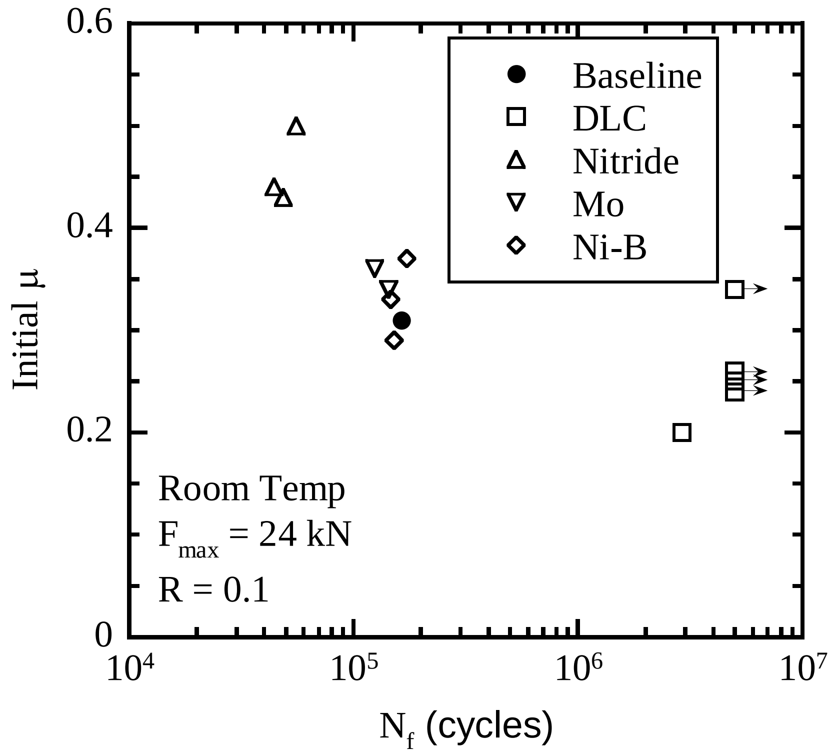

Figure 6: Dovetail fretting fatigue test results plotted in terms of initial average coefficient of friction versus life to failure [14].

It is well known that the average coefficient of friction, μ, is not necessarily equal to the coefficient of friction in the slip zone. In many materials, including Ti-6Al-4V, μ increases with total slip. It is expected, therefore, that when in a partial slip condition the μ in the slip zone would be higher than the average value. This has been shown by other researchers through carefully designed experiments and analysis [22]. Based on this work, a value of 0.7 was chosen for μ in the slip zone for the stress analysis of the baseline (no surface treatments) tests. The actual test data is plotted in Figure 7 versus the predicted total life for these tests. When the same slip zone coefficient of 0.7 is used to calculate the lives of the DLC coated specimens, however, the total life was greatly under predicted as shown in the figure. The analysis was then repeated using the average DLC coefficient of friction of 0.25 for the slip zone. This assumption is supported by tribological data generated as part of this test program which shows that DLC coated Ti-6Al-4V can maintain a low μ under a reciprocating sliding fretting test whereas the bare Ti-6Al-4V had a significantly increased μ under the same test conditions. Details of this test procedure can be found in Hager et al. [25]. The predicted lives using the lower μ are greatly improved and are also plotted in Figure 7. Four of the five DLC coated tests were 5 million cycle runouts and the analysis predicted no crack growth in two of those tests. The other two runout tests were predicted to fail in approximately 3-5 million cycles. The fifth test failed in 2.9 million cycles while the analysis predicted a 3.3 million cycle failure. In addition to total life prediction, the calculated fraction of total life spent in crack nucleation can be determined from the analysis. For the baseline tests that fraction ranged from 7% to 16%. The fraction of predicted life spent in nucleation when the specimens are coated with DLC increased to approximately 45%. This supported the presumption that a larger proportion of the increased life due to the DLC coating would be due to crack nucleation rather than crack growth.

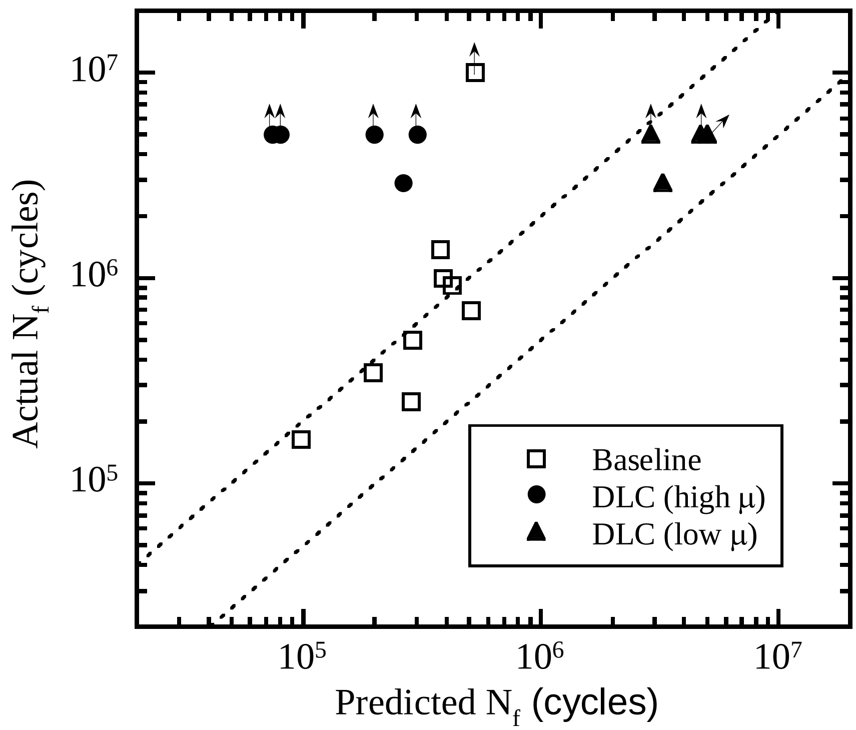

Figure 7: Life prediction results of baseline tests and DLC coated specimens. A comparison of life calculation with high or low slip zone coefficient of friction is shown.

The same type of analysis was repeated for the tests that were processed with LSP or LPB. Since the material pair in these tests had not changed, the same value of 0.7 for μ was assumed. Initially these tests were analyzed without accounting for the compressive residual stresses induced by LSP or LPB. The actual test data is plotted in Figure 8 versus the predicted total life for these tests. The predictions are overly conservative, showing that the presence of the residual stresses significantly influences the life. The analysis was then repeated with the residual stresses superposed onto the calculated stress solution prior to performing the nucleation and propagation analyses. All six of the tests were predicted to not fail due to crack arrest. In the actual test results, however, three tests failed leading to the conclusion that this analysis procedure was anti-conservative. It was believed that the high local stresses, tensile and compressive, led to localized yielding and relaxation of the residual stress. The relaxed residual stress state would lead to shorter predicted lives. The predicted nucleation life fraction for these tests was less than 1% of total life. This very low fraction occurs because the analysis shows very little change in nucleation life due to the presence of compressive residual stresses, but a large increase in propagation life. The deep compressive residual stress acts to close the crack and greatly reduce the stress intensity factor range. Finally, the testing of specimens processed with LSP or LPB and coated with DLC were analyzed using a low value of μ and superposing the compressive residual stresses. These results are plotted in Figure 9 along with all of the final analysis results. Similar to the LSP or LPB tests with no coating, the tests were predicted to never fail, however one of the six tests did fail. In these tests the predicted nucleation life was an order of magnitude greater than the actual runout life of 2 to 4 million cycles. Likewise, if the presence of a small crack was assumed the crack was predicted to arrest.

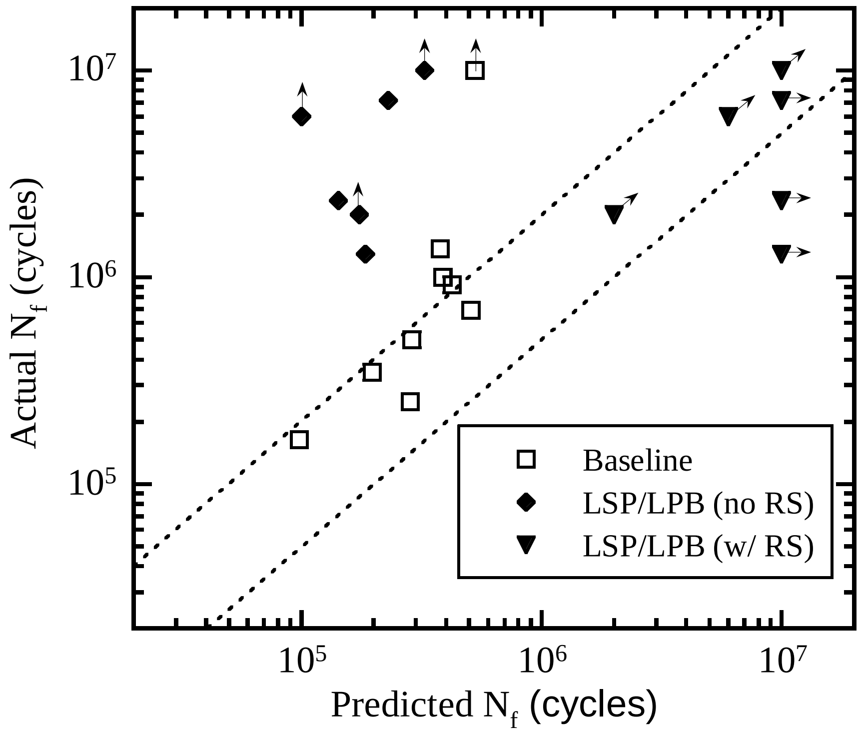

Figure 8: Life prediction results of LSP or LPB treated specimens. A comparison of results with and without the superposition of residual stresses is shown.

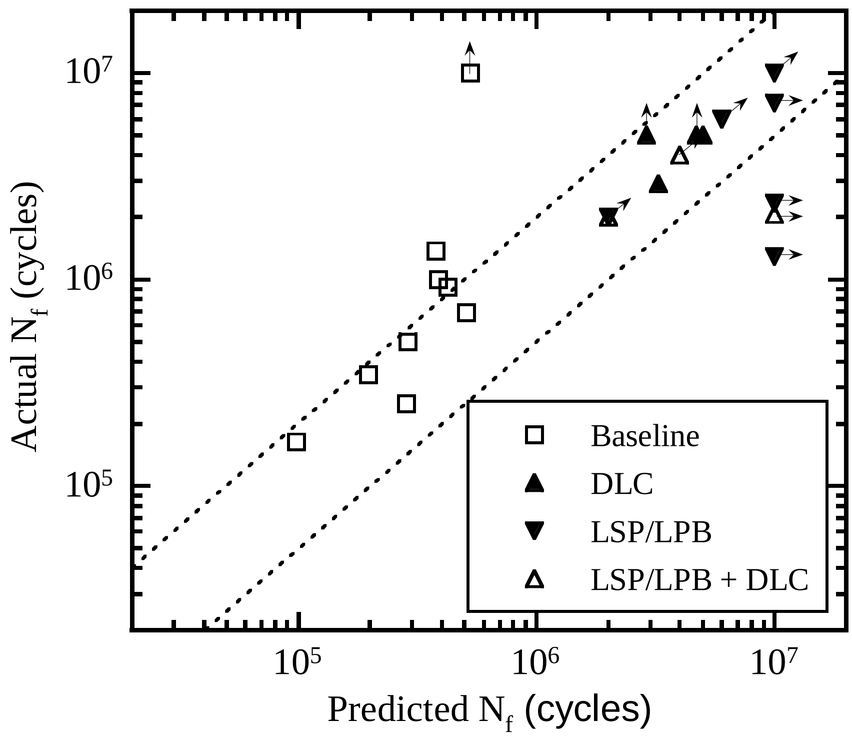

Figure 9: Life prediction results of all tests with low coefficient of friction assumption for DLC coated specimens and superposition of residual stresses for LSP and LPB treated specimens.

Finally, some of the fretted surfaces were analyzed in more detail through examination of the fracture surfaces, visual examination of the fretting scars, profilometry of the fretting scars, and polishing along the cross-section of the fretting scar. Figures 10 and 11 are fretting scars from two different tests. Figure 10 is from a test conducted with no coatings or surface treatments. This particular test was a runout so a large through crack was not present at the trailing edge of contact (bottom edge). The slip zone is visible in the photograph as a dark line across the bottom of the scar, a wide band across the right side, a very thin line across the top, and it is very difficult to see along the left edge. This scar was typical of a test conducted nearly entirely in the partial slip condition with the ratio of shear to normal force well below the average value of μ. Figure 11, however, was from a DLC coated specimen and appears to have a large slip zone around the entire contact region with a small stick zone in the center of the contact. This scar was indicative of a test that had a shear to normal force ratio close to the average value of μ. This supports the assumption used in the analysis that the slip zone coefficient of friction in the DLC coated specimens does not drastically increase through the course of the test. Some of the other results were inconclusive, however, scanning electron microscopy of runout tests from specimens processed with LPB have shown surface cracks at the edge of contact that did not grow to failure. This supports the analysis which shows that the presence of compressive residual stresses were not likely to stop crack nucleation, only crack growth.

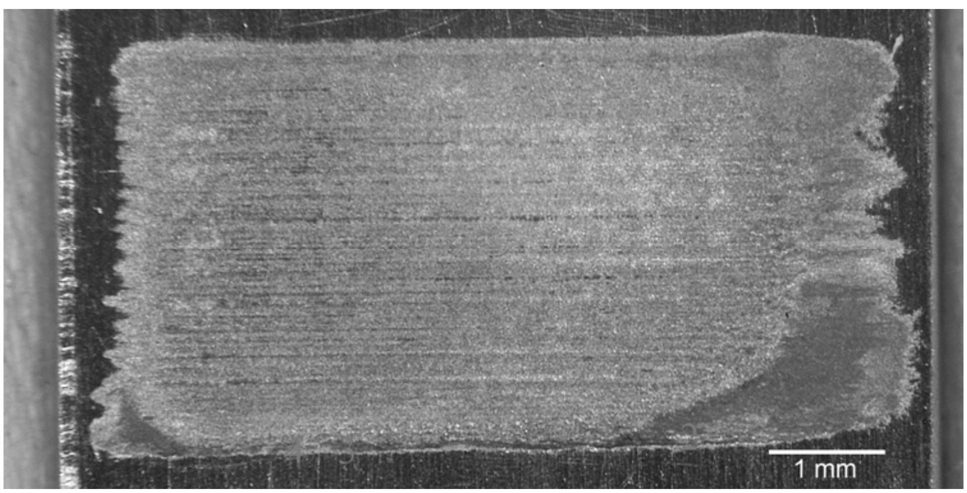

Figure 10: Typical fretting scar of a specimen with no coatings. Note the racetrack type pattern around the edge of contact indicating the slip zone.

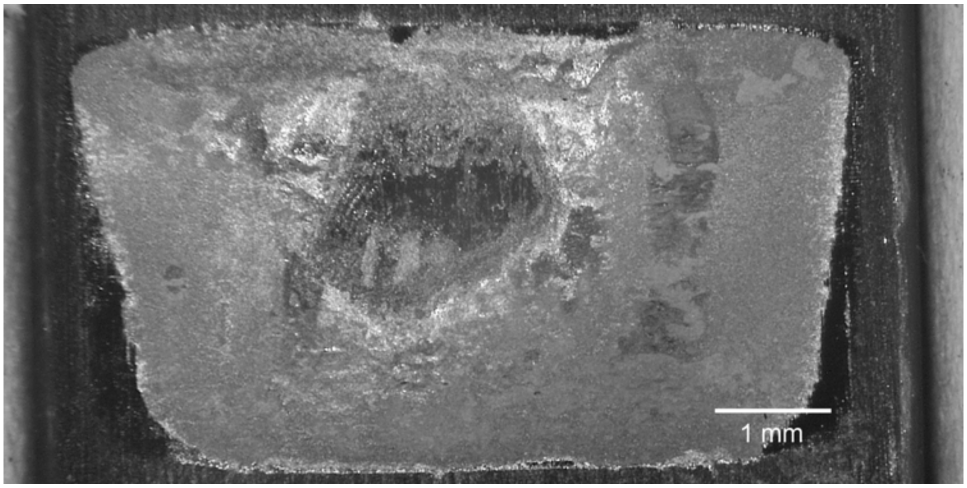

Figure 11: Fretting scar of a specimen with a DLC coating. Note the very large apparent slip zones and small region of stick in the center of the contact patch.

5. Conclusions

Several conclusions can be made as a result of this work. First, an efficient methodology is available to conduct a contact stress analysis necessary to calculate life without relying entirely on the finite element method. A relatively coarse finite element method combined with the singular integral equation method is sufficient to obtain accurate stresses in the very high stress gradient region at the edge of contact and account for the boundary conditions of the actual problem. Second, life prediction analysis and experimental observations show that various palliatives are effective at extending the fretting life for different reasons. Low friction coatings can work by reducing the magnitude of the applied loading in a dovetail attachment and by reducing the peak stresses at crack nucleation sites. This effects life primarily by increasing the number of cycles needed to nucleate a crack. Surface processing that induces compressive residual stresses such as low plasticity burnishing and laser shock processing extend life by significantly reducing the stress intensity factor range resulting in slowed crack growth or crack arrest. Analysis and experimental observations show that these processes do not eliminate the nucleation of cracks due to fretting.

Acknowledgements

The coatings and surface treatments provided by the vendors Diamonex, Universal Chemical Technologies, Southwest Research Institute, Cincinnati Thermal Spray, LSP Technologies, and Lambda Technologies are also gratefully acknowledged. The authors also thank Mr. Jeremy Tumpak for his metallography and microscopy work. Thanks also to Lambda Technologies for providing the residual stress measurements.

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