Improved High cycle fatigue Damage Tolerance of Turbine Engine Compressor Components By Low Plasticity Burnishing (LPB)

Paul S. Prevéy
Lambda Technologies
3929 Virginia Avenue, Cincinnati, Ohio 45227
United States
Phone: 513.561.0883, Fax: 513.561.0886
E-mail: pprevey@lambdatechs.com

N. Jayaraman
Lambda Technologies
3929 Virginia Avenue, Cincinnati, Ohio 45227
United States
Phone: 513.561.0883, Fax: 513.561.0886
E-mail: njayaraman@lambdatechs.com

Ravi A. Ravindranath, Propulsion & Power
NAVAIR
22195 Elmer Rd., Patuxent River, Maryland
20670-1534, United States
Phone: 301.757.0472, Fax: 301.757.0562
E-mail: ravi.ravindranath@navy.mil

Dr. Michael Shepard
WPAFB AFRL/MLLMN
2230 10th Street, WPAFB, Ohio 45433-7817
Phone: 937.255.1384, Fax: 937.656.4840
United States
E-mail: Michael.Shepard@wpafb.af.mil

ABSTRACT

Significant progress has been made in the application of low plasticity burnishing (LPB) technology to military engine components, leading to orders of magnitude improvement in damage tolerance. Improved damage tolerance can facilitate inspection, reduce inspection frequency, and improve engine operating margins, all leading to improved military readiness at significantly reduced total costs. Basic understanding of the effects of the different LPB process parameters has evolved, and finite element based compressive residual stress distribution design methodologies have been developed. By incorporating accurate measurement of residual stresses to verify and validate processing, this combined technology leads to a total solutions approach to solve damage problems in engine components. An example of the total solution approach to develop LPB processing of a 1st stage Ti-6Al-4V compressor vane to improve the foreign object damage (FOD) tolerance from 0.002 in. to 0.025 in. is presented. The LPB process, tooling, and control systems are described, including recent developments in real-time process monitoring for quality control. Performed on CNC machine tools, LPB processing is easily adapted to overhaul and manufacturing shop operations with quality assurance procedures meeting military and industry standards, facilitating transition to military depots and manufacturing facilities.

INTRODUCTION

Turbine engine compressor components such as blades, vanes, integrally bladed rotors (IBRs) or bladed disks (blisks) are prone to high cycle fatigue (HCF) and FOD at critical locations on the leading and trailing edges. Some fan and compressor components have a FOD tolerance of less than 0.005 in., and consequently require extensive inspection, rework, and replacement. Dovetail regions of the compressor blades and dovetail posts of the compressor rotors are also prone to fretting induced microcracking. Inspections of such microcracks are very cumbersome and difficult, often involve very complex and expensive instruments, and highly trained personnel. Typically compressor vanes and blades cost several thousand dollars each and rotors cost several tens of thousands of dollars. Costs of an IBR or blisk could run into hundreds of thousands of dollars. HCF accounts for 56% of major aircraft engine failures, and ultimately limits the service life of most critical components[1]. An estimated $400 million is expended annually for HCF related inspection and maintenance, greatly increasing the total ownership cost of military aircraft. The associated reduction in time-on-wing increasingly impacts military readiness. Considering all these factors, increased damage tolerance for these critical components will lead to substantially reduced early retirement of components, ease of inspection, less frequent and less expensive inspection and maintenance and therefore significantly improved military readiness.

The deep stable layer of compressive residual stress produced by LPB[2,3,4] has been demonstrated to produce remarkable improvement in damage tolerance, corrosion fatigue, and fretting in a variety of materials. Damage tolerance in IN718,[5] Ti-6Al-4V,[6,7], Ti-6-2-4-6[8], 17-4PH,[9] and Custom 450,[10] have been studied extensively in laboratory coupons. Mitigation of corrosion pitting damage in aluminum[11] and steel,[12] and active corrosion in aluminum[13] have been reported. Application of LPB to produce through-thickness compression in the leading edge of a rotating engine component, Ti-6Al-4V first stage fan blade, produced an order of magnitude improvement in damage tolerance.[14] These developmental test

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programs have led to the compilation of a large database on many different alloy systems supporting the application of LPB induced compression to combat a variety of damage conditions in turbine engine components.

By means of theoretical modeling,[15,16] a clear understanding of the magnitude and depth of compressive residual stresses required to mitigate damage while addressing other design-related issues like part distortion has been developed. Tool design and real-time process quality assurance (QA) have been fully addressed. Through these efforts, a simple new philosophy for turbine engine life extension and life management has emerged. The traditional approach to mitigate damage and improve HCF performance of a turbine-engine component is to either change the design or the material, both very time-consuming and expensive undertakings. The new fatigue enhancement design approach is to introduce appropriate compressive residual distributions at critical locations to cancel applied tension and mitigate damage mechanisms. This design approach is based on the use of fatigue design diagram (FDD) to determine the optimum level of compression needed for mitigating the amount of damage quantified by the effective fatigue stress concentration factor, k_f. Using the optimum residual stress as the target, LPB processing parameters and CNC control code are developed, and the resulting residual stress distribution is measured on actual components using x-ray diffraction ($\sin^2\psi$ method). The measured residual stresses are then input into a finite element model (FEM) of the component to determine the net distribution of residual and applied stresses. Finite element Analysis (FEA) is used during design of the residual stress distribution to determine the distribution of compensatory tension and to limit the distortion to the design tolerances. Once the desired residual stress distribution is achieved, components are LPB treated for fatigue testing. Processing quality assurance (QA) is implemented by real-time monitoring, recording, and controlling of the LPB process parameters. In this paper, a brief description of the fatigue design diagram is presented in the next section, followed by the application of the total solution methodology to improve the FOD tolerance of a 1st stage compressor vane from <0.002 in. to 0.025 in. using LPB.

FATIGUE DESIGN DIAGRAM

Following Lambda's LPB Development Protocol, the failure analysis and material characterization were completed followed by the design of a specific compressive residual stress distribution for the component. The compressive distribution is designed using the fatigue design diagram (FDD).[17] The FDD is a novel extension of the Haigh (or Goodman) diagram to include the region of compressive mean stresses. Unlike the Goodman line, the Smith-Watson-Topper (SWT) model is used to account for the variation in the fatigue strengths at various mean stresses for a given fatigue life, say 10^7 cycles. When damage is accounted for by Neuber-type stress concentration factor (k_t) or more appropriately, k_f, the fatigue stress concentration factor, a series of SWT lines can be drawn in the modified Haigh diagram or FDD. This FDD can then be used for predicting fatigue behavior incorporating the residual stress states existing in the component. The FDD predicts a safe region in which mode I cracking is not possible. When operating in this region, damage conditions like FOD, fretting-induced shear microcracks, corrosion pits, etc., will not transition into propagating fatigue crack. This allows the design of compressive residual stress distributions to mitigate a specific damage conditions for a given component and applied stress field. For example, Figure 1a shows the fully constructed FDD for Ti-6Al-4V with confirming fatigue data. Figure 1b demonstrates the use of FDD to design the correct magnitude of compressive residual stresses for fully restoring and enhancing the fatigue performance of a damaged part operating at R=0.1 with damage producing a k_f=3. Residual stress distributions for the part geometry, critical location, and damage conditions were then designed using the FDD for Ti-6Al-4V. The designed residual stresses were then incorporated into finite element models of the part to determine the magnitude and locations of compensatory tension and the –distortion caused by the introducing the compression.

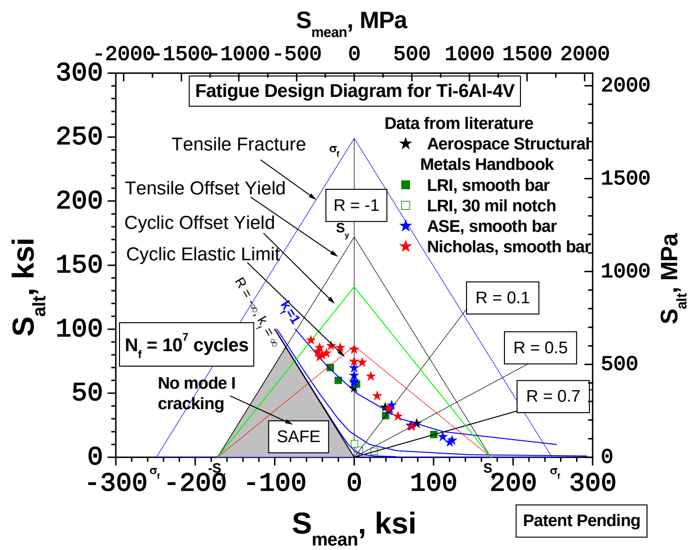

Figure 1a – FDD for Ti-6Al-4V

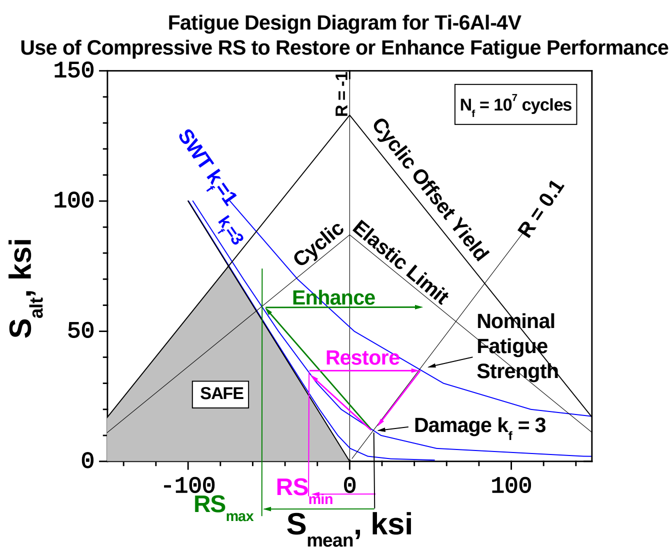

Figure 1b. Demonstration of the use of FDD

DESIGN PROCESS

Figure 2 shows a photograph of the Ti-6Al-4V 1st stage compressor vane, with an arrow indicating the affected region. The vane is prone to cracking at the high stress location on the trailing edge (TE) near the platform, and is FOD-limited in service to no more than 0.002 in. at the critical location.

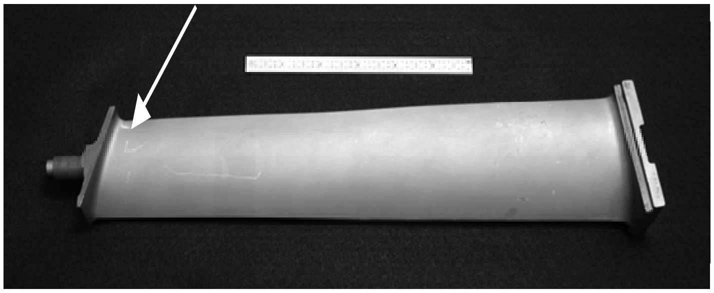

Figure 2. The Ti-6Al-4V compressor vane with FOD limited trailing edge. The arrow indicates the region sensitive to foreign object damage (FOD)

Quantitative measure of damage is possible by empirically determining the fatigue stress concentration factor (k_f) associated with each damage condition. In Figure 3, the fatigue strengths for 10^7 cycles are plotted to estimate k_f as the ratio of the fatigue strength of the smooth bar (undamaged state) over the damaged state. In the example shown here, the damage was simulated using EDM (electrical discharge machining) notches in Ti-6Al-4V blade-edge specimens simulating the features of the TE of the 1st stage compressor vane. EDM notches, with a cracked recast layer in residual tension at the bottom of the notch were chosen as a worst-case condition for simulated FOD. EDM notches ranging in size from 0.020 to 0.060 in. were used. The EDM notch of 0.020 in. corresponds to a k_f of nominally 10. Note that the effect of introducing residual compression, shown by the LPB treated blade-edge feature specimen in Figure 3, provides tolerance of even a 0.060 in. notch that is much better than the baseline (untreated) specimen with only 0.020 in. notch.

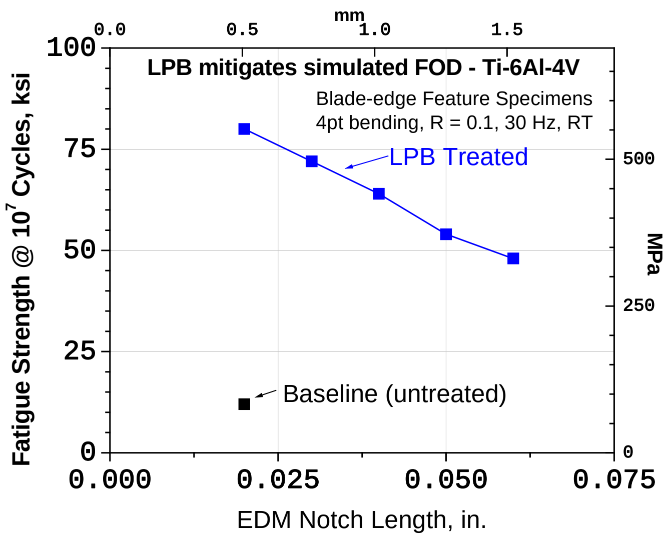

Figure 3. Effect of simulated FOD on the fatigue strength of feature specimens of Ti-6Al-4V compressor vane

The stress state at the crack tip is represented in an FDD in Figure 4, an optimum design compression of about –45 ksi at the weakest point in the component is predicted. That is, compressive residual stresses of this magnitude at the bottom of the FOD in the mid-thickness point of the vane will fully mitigate the effects of 0.020 in. FOD, restoring the allowed alternating stress.

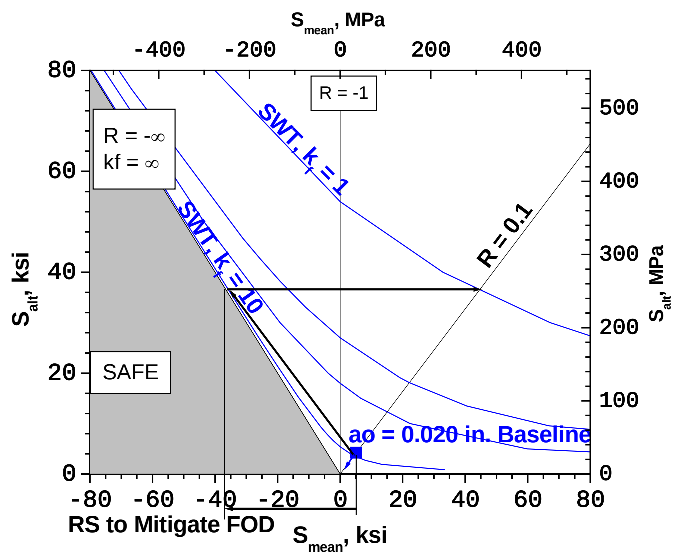

Figure 4. A magnified version of the Ti-6Al-4V FDD for simulated FOD of 0.020 in. in blade-edge specimens.

Using the design, LPB processing parameters and CNC code were developed, and vanes were LPB processed to produce the designed residual stress field. Figure 5 shows the measured residual stress distribution in the form of a stress contour map superimposed upon the outline of the LPB zone. The compressive residual stress field was then input into an

FEM and analyzed to determine the location and magnitude of compensatory tensile stresses.

The vane was meshed in ANSYS using parabolic hexahedral (20 node brick) elements. Eight elements were used to model through the thickness of the TE (trailing edge) in the LPB region and beyond, including into the inner platform blend. The remaining areas of the vane were meshed using parabolic (10 noded) tetrahedral elements. ANSYS has pyramid elements to transition between hexahedrons and tetrahedrons. Critical areas such as the platform blend, was pre-meshed with surface elements to control the mesh spacing and force the underlying solid elements to conform to the surface geometry. The surface pre-mesh elements were deleted before solution. The model consisted of a total of 150272 nodes with 450816 degrees of freedom. A Linear Elastic material model was used.

The results from FEA are shown in the form of stress contours in Figure 6. In this figure, the LPB-induced residual stresses and the compensatory tensile stresses are shown. The tensile stresses are designed to be located at regions that see very little service stresses and are remote from FOD. FEA also helped determine the inevitable distortion due to the introduction of the compressive zones, and to adjust the design to keep the distortion within design tolerances.

After confirming that the optimum LPB condition had been achieved by residual stress measurement, additional vanes were LPB treated and fatigue tested. For this purpose, fielded and retired vanes with unknown service history were available for testing. Randomly selected vanes were LPB treated and fatigue tested in a Sonntag SF-1U machine. The test set up is shown in Figure 7 with the truncated vane loaded in cantilever bending mode. All the vanes were tested at a stress ratio, R of 0.1, frequency of 30Hz at room temperature. A group of baseline and LPB treated specimens with 0.020 in. deep EDM notch to simulate FOD conditions were also tested.

The high cycle fatigue results from the vane tests are shown in Figure 8. The benefits of LPB are evident. LPB processed vanes, either with or without 0.020 in. FOD, showed 10^7 cycles fatigue strength of over 100 ksi at R = 0.1. Subsequent engine tests conducted by the OEM on vanes with ballistic FOD have further confirmed these results. Figure 9 shows the FDD with the test result from Figure 8 plotted.

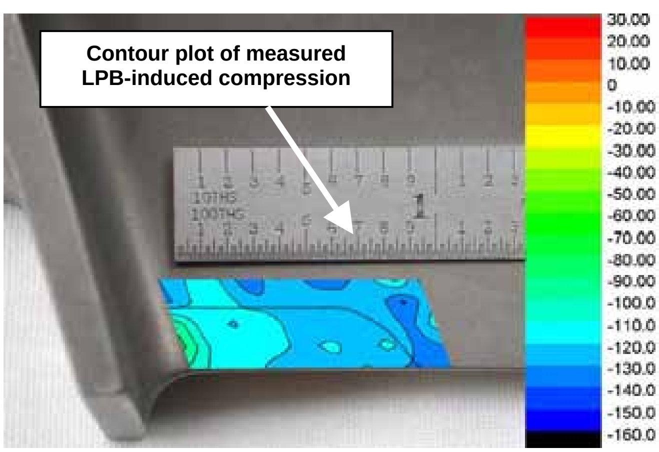

Figure 5. LPB-induced compressive residual stress distribution on the TE of Ti-6Al-4V compressor vane shown in the form of a contour plot.

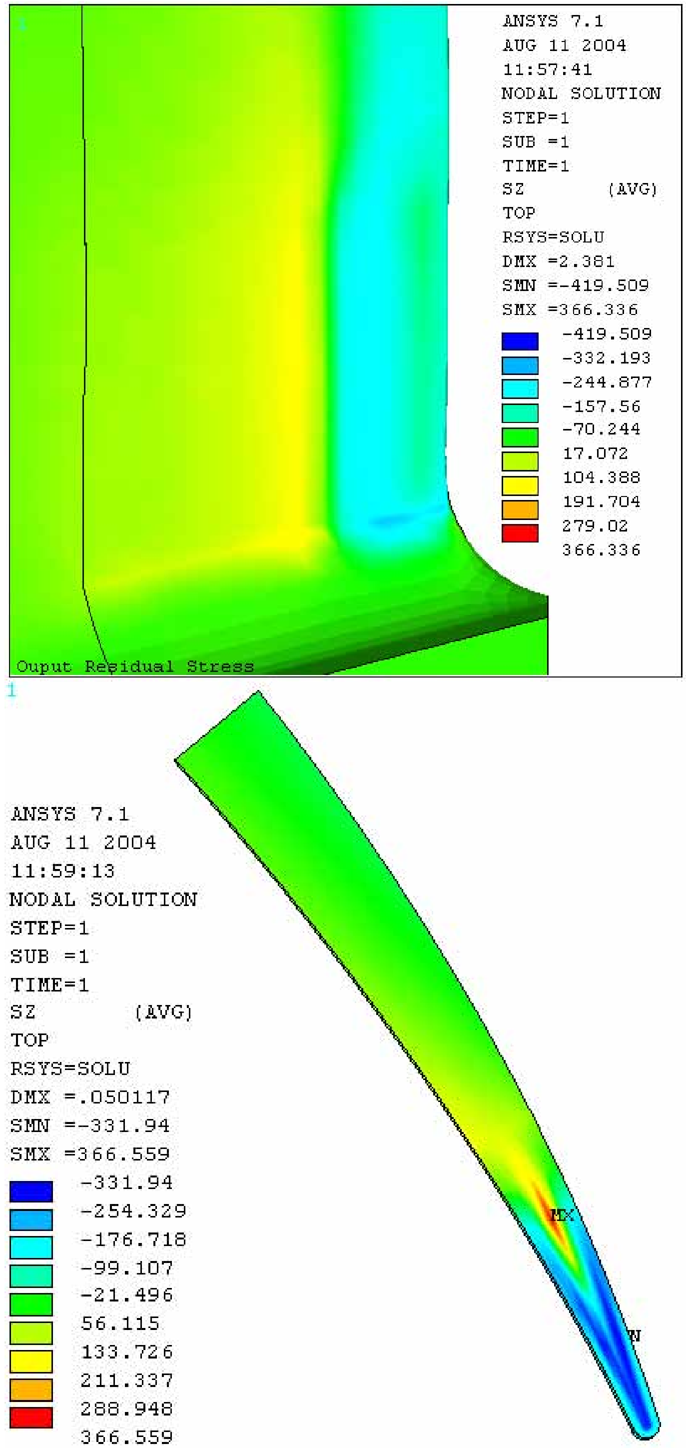

Figure 6. Stress contours showing the location and magnitude of compensatory tension due to LPB-induced compression on the TE of Ti-6Al-4V vane.

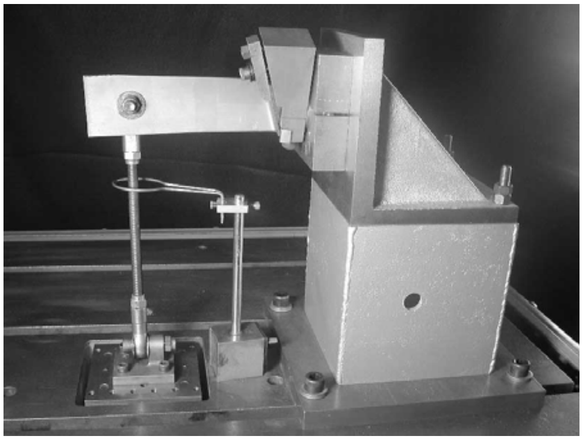

Figure 7. Photograph showing the fatigue test set up for Ti-6Al-4V compressor vane TE in a Sonntag SF-1U fatigue machine in cantilever loading.

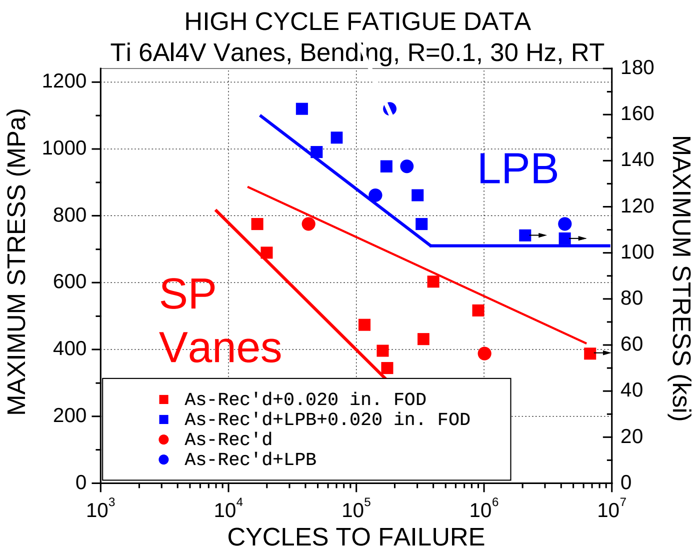

Figure 8. Fatigue test results for Ti-6Al-4V compressor vane comparing LPB processed and shot peened (SP) vanes taken from service. Scatter in the SP vane is attributed to widely distributed field generated FOD.

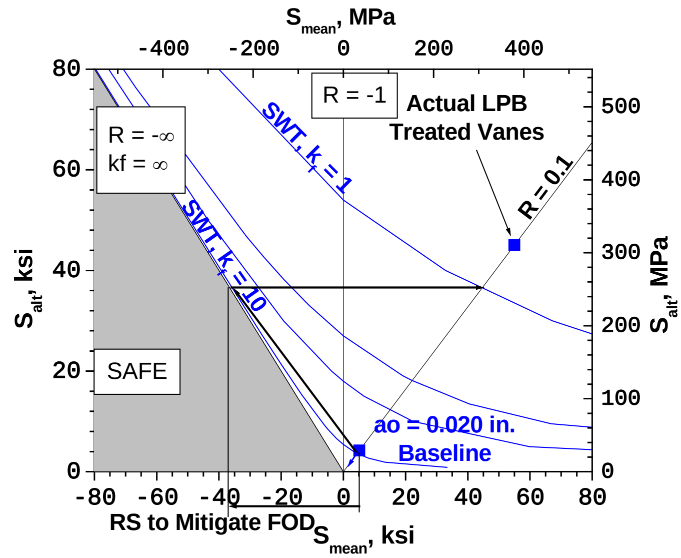

Figure 9. FDD for the Ti-6Al-4V vane with the test result for the LPB treated vane plotted.

PROCESSING OF COMPONENTS AND QUALITY ASSURANCE

Based on the determination of optimal compressive residual stress distribution, production LPB processing tooling and shop routing for serviceable vanes were develop for a five-axis CNC milling machine. The fixture and the caliper tool developed are shown in Figure 10. The primary process variables are dynamically controlled, monitored, and recorded in computer files for QA purposes and statistical process control (SPC). The closed-loop control assures the operation parameters are kept within the specified window, and if rare deviations beyond the specified window occur, the exact location and magnitude of deviation are marked and the component is tagged for further investigation and appropriate corrective actions. Figure 11 shows that the typical variations seen in the process parameters are well within 1% of the set point, while the QA window processing window of 16% is allowed, providing a robust and real-time monitored process.

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Figure 10. Photograph showing the LPB process set up in a 5-axis CNC milling machine with a caliper tool set ready for LPB processing of the TE of a Ti-6Al-4V compressor vane.

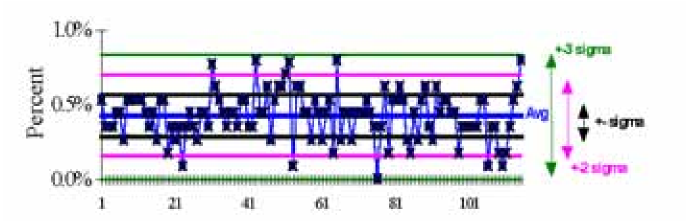

Figure 11. Typical plot of the variation at every step of the vane LPB processing showing a range within 1% for processing window of +-16%.

SUMMARY AND CONCLUSIONS

A comprehensive design methodology, based on the fatigue design diagram (FDD) for designing optimal compressive residual stress distributions for the critical regions of turbine engine compressor components has been presented. This methodology integrates the FDD approach with FEA to design complex compressive residual stress fields for turbine engine components. When combined with the capabilities for accurate measurement of residual stresses for process verification and fatigue testing for validation, the proposed design method provides an attractive approach to solve fatigue damage problems in engine components. The method has been successfully applied to improve the foreign object damage (FOD) tolerance of a Ti-6Al-4V compressor vane from 0.002 in. to 0.025 in. using LPB processing to introduce through-thickness compression in the region of high applied stress on the trailing edge of the vane.

REFERENCES

1. Propulsion Directorate, AFRL/WPAFB (2000), High Cycle Fatigue (HCF) Program 1999 Annual Report, AFRL-PR-WP-TR-2000-2004
2. T. Gabb, J. Telesman, et.al., “Surface Enhancement of Metallic Materials”, *Advanced Materials & Processes*, ed. Peg Hunt, ASM, Materials Park, OH, January 2002, pg. 69-72.
3. “Longer Life with Low Plasticity Burnishing”, *Manufacturing Engineering*, ed. Brian Hogan, SME, December 2001, pg. 34-38.
4. U.S. Patents No. 5,826,453 (Oct., 1998) and 6,415,486 (Jul., 2002), other US and foreign patents pending.
5. Paul S. Prevéy, et.al., "FOD Resistance and Fatigue Crack Arrest in Low Plasticity Burnished IN718", Proceedings of the 5th National High Cycle Fatigue Conference, (2000). IN718
6. Paul S. Prevéy, et.al., “The Effect of Low Plasticity Burnishing (LPB) on the HCF Performance and FOD Resistance of Ti-6Al-4V,” Proceedings: 6th National Turbine Engine High Cycle Fatigue (HCF) Conference, Jacksonville, FL, March 5-8, 2001.
7. M. Shepard, P. Prevéy, N. Jayaraman, “Effect of Surface Treatments on Fretting Fatigue Performance of Ti-6Al-4V,” Proceedings 8th National Turbine Engine HCF Conference, Monterey, CA, April 14-16, 2003.
8. P. Prevéy, N. Jayaraman, M. Shepard, “Improved HCF Performance and FOD Tolerance of Surface Treated Ti-6-2-4-6 Compressor Blades,” Proceedings 9th National HCF Conference, Pinehurst, NC, Mar. 16-19, 2004.
9. P. Prevéy, N. Jayaraman, R. Ravindranath, “Low Plasticity Burnishing (LPB) Treatment to Mitigate FOD and Corrosion Fatigue Damage in 17-4 PH Stainless Steel,” Proceedings Tri-Service Corrosion Conference, Las Vegas, NV, Nov. 17-21, 2003.
10. N. Jayaraman, P. Prevéy, “Application of Low Plasticity Burnishing (LPB) to Improve the Corrosion Fatigue Performance and FOD Tolerance of Alloy 450 Stainless Steel,” Proceedings Tri-Service Corrosion Conference, Las Vegas, NV, Nov. 17-21, 2003.
11. Paul S. Prevéy and John T. Cammett, “The Influence of Surface Enhancement by Low Plasticity Burnishing on the Corrosion Fatigue Performance of AA7075-T6,” Proceedings 5th International Aircraft Corrosion Workshop, Solomons, Maryland, Aug. 20-23, 2002.
12. P. Prevey, N. Jayaraman, N. Ontko, M. Shepard, R. Ware, J. Coate, “Mechanical Suppression of SCC and Corrosion Faitgue Failures in 300M Steel Landing Gear,” Proceedings of ASIP 2004, Memphis, TN, Nov. 29 to Dec. 2, 2004.
13. Paul S. Prevéy and John T. Cammett, “Restoring Fatigue Performance of Corrosion Damaged AA7075-T6 and Fretting in 4340 Steel with Low Plasticity Burnishing,” Proceedings 6th Joint FAA/DoD/NASA Aging Aircraft Conference, San Francisco, CA, Sept 16-19, 2002
14. Paul S. Prevéy, Doug Hornbach, John Cammett, and Ravi Ravindranath, “Damage Tolerance Improvement of Ti-6-4 Fan Blades with Low Plasticity Burnishing,” Proceedings 6th Joint FAA/DoD/NASA Aging Aircraft Conference, San Francisco, CA, Sept 16-19, 2002.
15. P. Prevéy, N. Jayaraman, R. Ravindranath, “Incorporation of Residual Stresses in the Fatigue Performance Design of Ti-6Al-4V,” Proceedings International Conference on Fatigue Damage of Structural Materials V, Hyannis, MA, Sept. 19-24, 2004.
16. P. Prevéy, N. Jayaraman, R. Ravindranath, “Use of Residual Compression in Design to Improve Damage Tolerance in Ti-6Al-4V Aero Engine Blade Dovetails,” Proceedings of the 10th Nat, HCF Conference, New Orleans, LA, March 8-11, 2005.
17. P. Prevéy, N. Jayaraman, R. Ravindranath, “Introduction of Residual Stress to Enhance Fatigue Performance in the Initial Design,” Proceedings Turbo Expo 2004, Vienna, Austria, Jun. 14-17, 2004.