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PERFORMANCE OF GEN IV LSP FOR THICK SECTION AIRFOIL DAMAGE TOLERANCE

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The General Electric Aircraft Engines Gen IV (low energy) laser shock peening (LSP) process is evaluated along a thick section of Ti 6Al-4V fan blade airfoil leading edge. Simulated foreign object damage (FOD) was imposed to assess the FOD tolerance improvement of the LSP treatment during high cycle fatigue (HCF) testing using an air siren. Data are presented for a total of 21 blade subarticles which were HCF tested to determine: (1) untreated baseline material capability without simulated FOD, (2) untreated material capability with simulated FOD and (3) LSP-treated material capability with simulated FOD. LSP-treated subarticles showed restored HCF capability and performed at the mean of the undamaged/untreated material capability with minimal variation within the population. Post-test fractography of the LSP test articles revealed fatigue crack initiation at the notch with crack propagation consistent with the fatigue strength measured. Crack initiation and propagation modes were further validated via optical and scanning electron microscopy. A further evaluation criterion was airfoil distortion due to the imposed residual stress. Post-LSP distortion data was evaluated via coordinate measurement machine inspection of all treated blades. The LSP-treated fan blades satisfied the distortion requirement. Conclusion of the study was that Gen IV LSP was able to provide the necessary notched HCF capability while still meeting airfoil distortion requirements.

NOMENCLATURE

ΔK_{th}	=	material threshold stress intensity factor
K_f	=	fatigue notch factor
R	=	stress or stress intensity ratio
K_{min}	=	minimum stress range stress intensity factor
K_{max}	=	maximum stress range stress intensity factor
ΔTT	=	change in airfoil section tangent angle
LSL	=	lower specification limit for ΔTT
USL	=	upper specification limit for ΔTT
K_t	=	theoretical stress concentration factor
q	=	notch sensitivity factor

INTRODUCTION

Gas turbine engines are susceptible to foreign object damage (FOD) due to ingestion of debris which impacts the gaspath turbomachinery. Damage typically occurs on the leading edge (LE) and produces nicks and/or tears that can lead to high cycle fatigue (HCF) failures during operation. Failures result from crack propagation if the damage geometry is severe enough to initiate cracks exceeding the material threshold stress intensity (ΔK_{th}) given the interaction of mean and modal stresses at the damage site. FOD produces an HCF knockdown (K_f) that must be managed via field maintenance activity by repair or replacement of the affected component. However, as operators desire to extend field maintenance intervals, serviceable damage limits (FOD that is acceptable to operate with) must be extended to reduce the need for repair and/or component replacement. The estimated costs due to FOD of approximately $4 billion annually[1] call for an ameliorating process to abate component failure due to FOD.

Laser shock processing has existed as a process for more than 30 years, having been pioneered at Battelle Laboratories in the early 1970's and first patented as a process to benefit material property behavior by Malozzi and Fairand[2]. Early studies showed the promise of laser shock processing over untreated/undamaged, untreated/damaged and treated/damaged Ti 6Al-4V blades, where various surface enhancement treatments were

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applied to regain fatigue capability in the presence of a notch by the imposition of residual stress and subsequent crack arrest (Fig. 1).

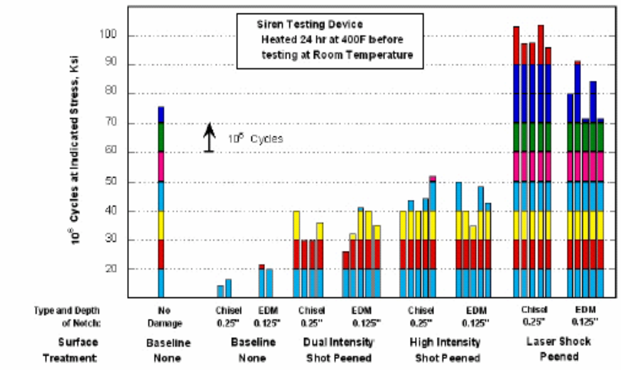

Fig. 1 Comparison of HCF capability for various conditions for a Ti 6Al-4V fan blade[3]

General Electric Aircraft Engines (GEAE) has expended significant time and resources over many years for the development and implementation of laser shock processing, ultimately resulting in the process known as laser shock peening (LSP). One application that GEAE has developed LSP for is the LE and tips of airfoils in order to abate fatigue failures and produce significant FOD tolerance. The use of LSP on an existing component increases serviceable limits without the need for airfoil redesign, thus maintaining the aerodynamic performance of the component. To date, GEAE has produced in excess of 50,000 LSP airfoils for US Air Force (USAF) applications such as stage 1 fan blades in the F101-GE-102 (B-1B Lancer) and F110-GE-100, -129 turbofans (F-16 Falcon, F-15 Strike Eagle). LSP is also incorporated onto the stage 1 fan blisk (bladed disk) for the F110-GE-132 turbofan engine (F-16 Block 60). These applications employ so-called Gen II technology, originally introduced in 1997 for the B-1B application. Gen II technology is based on custom-built laser systems at relatively high energies (up to 50J) typical of other processes examined in the literature[4]. Fatigue capability enhancement typical of GEAE's Gen II process is shown in Fig. 2.

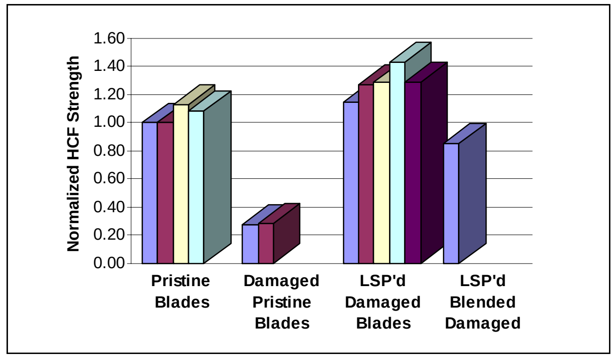

Fig. 2 Typical fatigue capability comparison for Ti 6Al-4V fan blades using GEAE's Gen II technology

LSP PROCESS OVERVIEW

The LSP process imposes residual compressive stress to the target area by focusing the laser beam on the target and vaporizing an ablative layer that is applied over the subject patch area (Fig. 3).

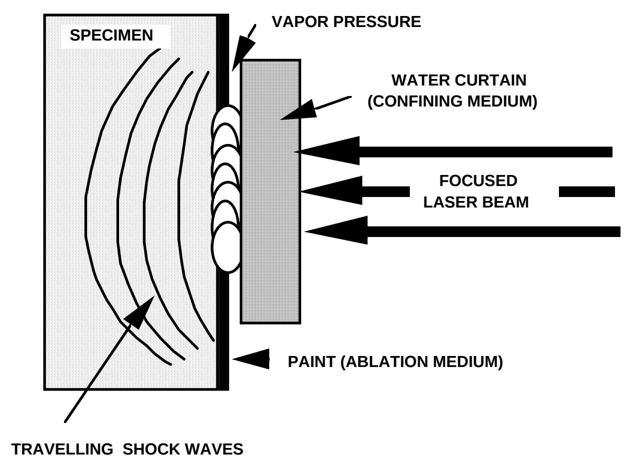

Fig. 3 LSP process overview[4]

Vaporizing the ablative layer produces a plasma under high pressure which is constrained by a confining medium (typically water). The confining medium reflects the pressure pulse back to the workpiece, propagating a shock wave through the piece. The shock wave plastically deforms the material ahead of it (in the thickness direction). Geometry constraints around the patch produce directional compressive loads/stress due to Poisson effects. It is this directional nature of the residual stress that, when correctly disposed counter to the prevailing principal stress field,

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can significantly retard crack propagation, yielding HCF strength improvements greater than 5x over untreated/damaged samples. The compressive residual stress profile through-thickness due to LSP is of greater depth than traditional shot peening, thus providing the crack arresting capability. Through-thickness compression is possible for thin section applications. Airfoils are typically processed using two-sided processing to abate distortion and enhance imposed residual stress.

The LSP process is very efficient in producing the compressive stress as compared to conventional shot peening, which is dependent on a random impact phenomenon to achieve the compression desired.

GE LSP LASER TECHNOLOGY OVERVIEW

The flight and safety critical F101-GE-102 and F110-GE-100/129 engine fan blade applications required GEAE to rapidly develop and deploy LSP to address USAF flight readiness needs. GEAE demonstrated between 1992 and 1994, using laser facilities at Battelle Memorial Institute, that LSP restored HCF capability and eliminated FOD sensitivity on fan blades as was shown in Fig. 2. The laser was a master oscillator power amplifier configuration (MOPA), q-switched neodymium doped YAG with eight individual laser heads, delivering 100J in 30 nanoseconds/pulse at a frequency of 0.1Hz. GEAE leased the first generation, or Gen I, laser equipment to further develop the process internally and have ready access for experimental work in parallel with Design Engineering analyses. Production was launched in 1997 at GEAE with the Gen I laser system and a multiaxis computer-numerical control (CNC) machine tool.

GEAE later contracted LSP Technologies, Inc. to design and build the first production units or Gen II systems (Fig. 4). The goal was to increase the throughput of the LSP systems by designing a laser that could deliver laser pulses to the target more rapidly than the Gen I system. The tradeoff was a more complex laser system (12 individual laser heads) with larger and more expensive components. The Gen II laser is also a MOPA Nd:glass laser: 100J in 30 nanoseconds at 0.25Hz. Three years of robustness projects by GEAE Manufacturing Engineering resulted in the Gen II system's typical 3 month maintenance cycles being extended to over 12 month cycles. Minor maintenance conducted weekly limits these machines to approximately 70% availability. Furthermore, the large size optics required (six inch mirrors and lens, glass rods up to 45mm in diameter) resulted in annual maintenance expenses of several hundred thousand dollars per system per year.

Fig.4 Gen II laser shock peen apparatus

The GE Gen III laser was a risk abatement project in concert with GE's Global Research Center in New York. The Gen III laser was again a Nd:glass system, but utilized slab technology versus the rods in Gen I and Gen II. The result was a system with a single head master oscillator and two amplifiers. The Gen III system is used to support ongoing process diagnostics and LSP developments. The Gen III was never implemented in production, as the robustness projects on the Gen II laser systems enabled those systems to be managed on a day-to-day basis.

The limitations of the above systems have been cost and technical complexity. The Gen I, II and III systems were significantly more expensive than an industrial drilling laser. This is because of the high energies they delivered and the requisite large components to generate 100J in the short pulse duration. Furthermore, the technical complexity of these systems required a user to establish a highly skilled maintenance staff. GEAE was able to accomplish this since a laser process and laser technology manufacturing group already existed within the Company. Even with an internal resource, however, the application of LSP has been limited to Cincinnati, OH where the manufacturing group can be near the equipment for the weekly and daily maintenance activities.

The key would then be to demonstrate that the LSP effect could be imparted using energies an order of magnitude lower than the above

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systems. This would enable the use of both alternative and commercial laser technologies. In 2000, GEAE Manufacturing Engineers reconfigured one of the Gen I lasers to produce a few Joules per pulse. The laser was focused into the processing cell and the spot size was set to maintain fluence on a flat titanium coupon as shown in Fig. 3. LSP impressions were evident on the surface, indicating that some level of compressive stress had been imparted. Larger areas on coupons were LSP'd with lower energies and destructively analyzed to measure stress as a function of depth from the surface. It was demonstrated that using lower energies, down to less than 5 Joules per pulse, compressive stress was imparted at depths up to 1.5mm (0.060 in.) or equivalent to Gen I and II LSP processes.

The ability to use lower energy to produce the LSP effect enabled GEAE to procure a commercial laser system that produces 10J in 30 nanoseconds at 10Hz. The investment cost for the laser system was significantly reduced while the throughput at equivalent fluence is greatly increased. The laser is serviced by an OEM network, freeing up the manufacturing lab resources to develop new processes and enable GEAE to install so-called Gen IV LSP systems (Fig. 5) for regional manufacturing needs.

Fig. 5 Gen IV laser shock peen apparatus

Once the first Gen IV prototype laser was installed at GEAE, the goal was to scale all production Gen II parameters down to the Gen IV energies, maintaining fluence from one process to the other. The Gen IV system was applied to the F101-GE-102 stage 1 fan blade with subsequent post-LSP distortion and HCF capability assessed. Fig. 6 shows the resulting HCF data over the ten-month development program.

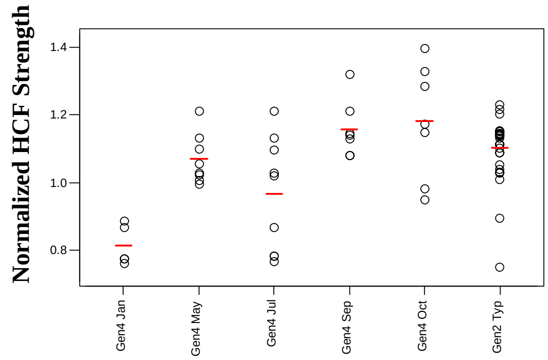

Fig. 6 Gen IV LSP development HCF data

The clusters of data in Fig. 6, from left to right, demonstrate the incremental improvement of the Gen IV process. The left hand results, which reflect the initial scaled Gen II parameters, exceeded minimum HCF. The next to last pair of results represent the final tuning of the Gen IV parameters for the F101-GE-102 stage 1 fan blade. The last group on the right is a representative population of one of the production Gen II lasers.

Thus, the Gen IV laser system had been demonstrated to be equivalent to the Gen II process in imparting the LSP effect with respect to distortion and HCF strength requirements. Furthermore, the development projects shown left to right in Fig. 6 resulted in Gen IV providing significant throughput improvement over the Gen II systems. The second Gen IV system is scheduled to come on line in 2Q04 and the single laser will allow the retirement of selected Gen II systems and still have excess capacity. The speed and simplicity of the systems, with investment costs under $1M per system for a Gen IV laser, will enable many new applications to be established cost effectively in the automotive, heavy industry and other areas of jet engines. The benefits of LSP will not be limited to critical components but can now be applied for improved performance and product life.

MECHANICS OF LSP FATIGUE CAPABILITY ENHANCEMENT

Both the measured fatigue strength benefit of LSP and the mechanisms via which LSP achieves this benefit are well documented in the literature. Ruschau et al.[5] demonstrated, for example, that it is the R-ratio shift achieved by the LSP-induced residual stress that creates the beneficial fatigue behavior. Given that a stress intensity R ratio is defined as:

$$R = \frac{K_{\min}}{K_{\max}} \quad (1)$$

where K_{min} and K_{max} are the minimum and maximum stress intensities at the crack tip, respectively, then, as Ruschau observes, an "effective" R ratio can be defined as follows:

$$R_{eff} = \frac{K_{\min,eff}}{K_{\max,eff}} = \frac{K_{\min} + K_{res}}{K_{\max} + K_{res}} \quad (2)$$

where a negative K_{res} (compressive) is used to describe the relative stress intensity across the crack tip due to the imposed compressive residual stresses. Hence, the compressive stresses of the LSP serve to shift the R_{eff}. This is made clear when evaluating fatigue crack growth rate properties of baseline (no LSP) and LSP-treated specimens in terms of applied ΔK. The benefit of LSP in shifting the data toward increased threshold stress intensity in Ti 6Al-4V at low R ratios has been well-documented.[5] Stated in another fashion, crack growth can occur only when K_{max} exceeds both K_{res} and the substrate material stress intensity threshold, ΔK_{th}.[5]

COMPONENT TEST PROCEDURE

The subject blades were Ti 6Al-4V alloy and representative of stage 1 military turbofan fan airfoils. Finite element analysis (FEA) was used to analytically predict modal strain distributions in order to assist in selecting candidate modes for bench (zero rotational speed) HCF testing. The stage 1 fan subarticles were tested in the first flexural (1F) mode (~450 Hz) to produce the necessary stress to fail the target LE location, which occurred at approximately 20% LE span (Fig. 7). HCF testing was accomplished on the bench using an air siren which applies the necessary stimulus consistent with the 1F mode frequency.

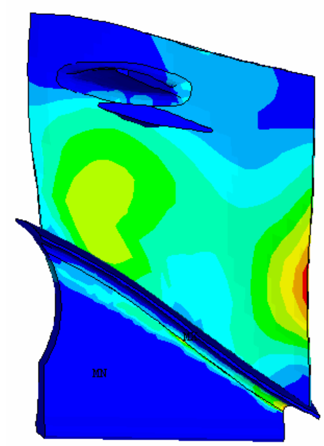

Fig. 7 Normalized effective stress contours for first flexural (1F) mode of fan blade subarticle

Blade subarticles were prepared by cutting off the outer airfoil panel (just outboard of the midspan shroud) to increase the test frequency and thus accelerate test time. Figs. 8 and 9 demonstrate the test setup.

Fig. 8 Blade subarticle setup for strain distribution/siren testing

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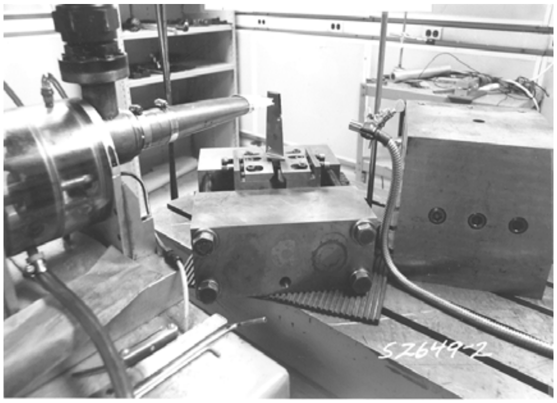

Fig. 9 Typical setup for strain distribution/siren testing

The stage 1 fan blade subarticles were tested to 10^7 cycles in stair-step fashion at R=-1. In this way, each subarticle was run to 10^7 cycles runout or failure. If 10^7 cycles were reached before failure was achieved, then the stress was increased and the subarticle was run again for another runout or failure. Starting stress levels for each subarticle, depending on configuration, were chosen consistently to target the same amount of runouts prior to failure in order to avoid excessive runouts and the risk of strain hardening the material. Subarticle airfoil stresses were measured using uniaxial strain gages placed consistent with a previously-performed full blade strain distribution. All laser shock peening, inspection, instrumentation and component testing were performed at General Electric facilities.

The component test plan to determine the FOD capability improvement of Gen IV LSP on these subarticles was as follows:

- Untreated/smooth blades
- Untreated/notched blades
- LSP/notched blades

HCF data from the configurations above determine baseline (smooth/untreated) blade strength while the notched/untreated blade data determines the fatigue knockdown (K_f) of the simulated FOD imposed on notched specimens (Fig. 10).

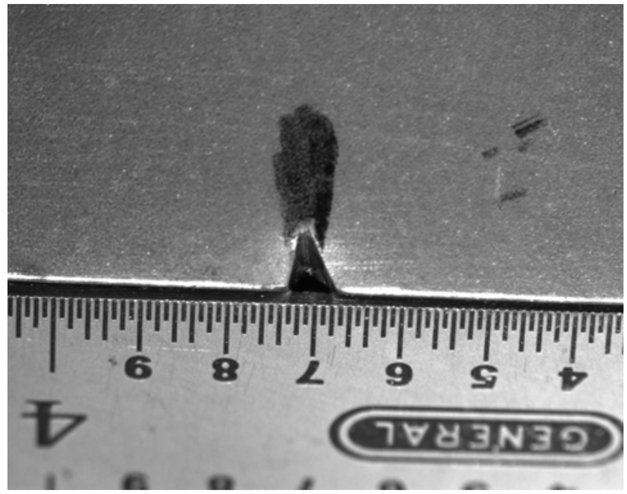

Fig. 10 Stage 1 fan blade subarticle sample notch used to simulate LE FOD

Notches were imposed via a MTS press outfitted with a chisel point. Unique tooling (Fig. 11) was manufactured to support the blades during notching so as to produce repeatable notches to provide the correct incidence angle of the chisel, consistent with expected FOD particle and blade tip speeds in the engine. Damage imposed in this fashion simulates observed operational field damage. Strain gages were placed at the notch on damaged subarticles to assist in determining the stress at the failure location.

Fig. 11 Fixture to secure fan blade for LE notching operation

Notches imposed for this study ranged from .06 to .10 inches in size. Notch size showed no direct correlation with resultant fatigue life, as Fig. 12 shows, and as expected for this notch size range based on substantial GEAE

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component test experience. Finally, it should be noted that subarticle instrumentation, notching and test procedures used in this study are entirely consistent with those applied to current Gen II-processed test pieces.

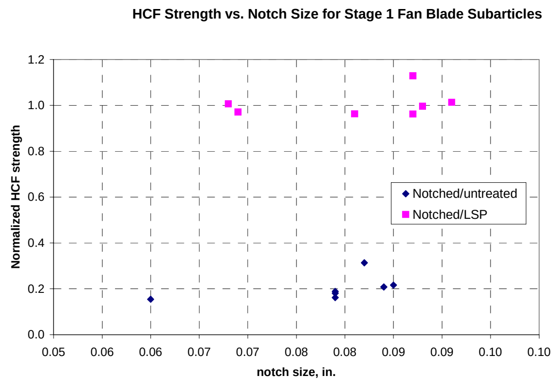

Fig. 12 Relationship of HCF strength versus imposed FOD notch size

Fig. 13 shows the chordal extent of the LSP patch applied to the subarticles in this study. The LSP patch width consistently measured .60 inches from the LE and spanned 85% of the LE (more than 10 inches) to provide significant maintainability/repairability for the subject blades in the field. LSP patches of this size and aspect ratio are recognized to be challenging with respect to managing airfoil distortion, given the propensity for large distortion and LE buckling. This is due to the fact that large spanwise loads can be generated over a column of rather thin cross section. As will be shown, LSP also performed well in terms of providing excellent HCF strength recovery with acceptable post-LSP distortion.

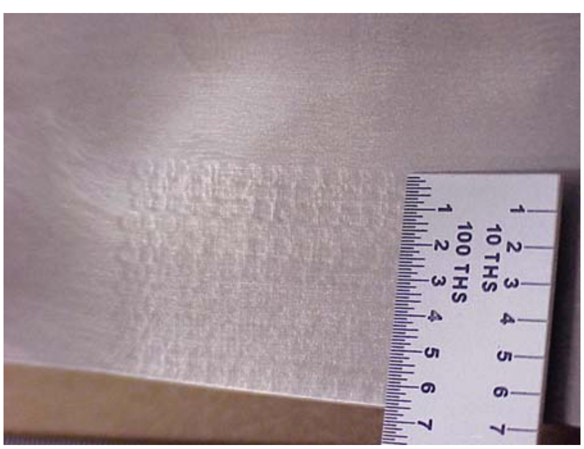

Fig. 13 Detail of LSP patch

LSP DISTORTION MANAGEMENT

Any residual stress process produces distortion due to the nonsymmetric geometry typical of gas turbine airfoils. Span and chordwise residual stresses produce deflections due to twist/bend coupling of the airfoil. Twist, in this context, refers to change of the individual airfoil section tangent angles post- versus pre-LSP. Airfoil geometry is controlled for manufacturing via definition at these planar sections. The tangent angle of each section dictates the incidence angle of that section to the gas flow at their respective section height and ultimately, fan performance. LSP distortion is managed, for example, by evaluating the magnitude of twist after LSP processing. The ability to apply the LSP process while minimizing distortion is central to retaining the necessary aerodynamic performance of the component. Excessive changes in tangent angle post-LSP can negatively impact engine mass flow, performance and stall margins. At the limit, excessive LSP fluence can also produce buckling distortion of the treated component. Patch placement, geometry and LSP process parameters are all important considerations in managing distortion. Trades must often be made to provide the necessary notched fatigue capability while minimizing the imposed post-LSP distortion.

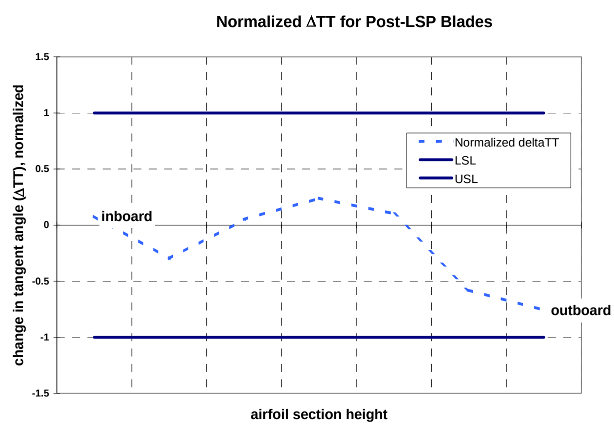

Fig. 14 Normalized change in airfoil tangent angle post-LSP for treated fan blades

Fig. 14 shows normalized results of tangent angle change (post-pre LSP) for the fan blades addressed in this study versus the limits for this distortion established by GEAE Aerodynamics engineers. Data for these blades were collected via coordinate measurement machine inspection of each airfoil section of the full-span blade prior to outer panel removal and reduced to calculate the change in airfoil tangent angle post-pre LSP. From Fig. 14, it is clear that LSP was successful in working within these constraints while simultaneously providing the necessary HCF strength.

IMPACT OF LSP ON NATURAL FREQUENCY

GEAE is currently investigating the effects of LSP on natural frequencies of treated components. FEA models have been developed to predict the shift in these frequencies, with these predictions validated on actual airfoils via ping hammer testing. Fig. 15 shows experimental data for a similar and representative fan blade illustrating the frequency shift post- versus pre-LSP. GEAE is also investigating the use of this frequency shift phenomenon for real time applications, such as on-the-fly process control, as part of the continual development of nondestructive evaluation methods of LSP toward eventually eliminating the need for regular fatigue testing during LSP processing.

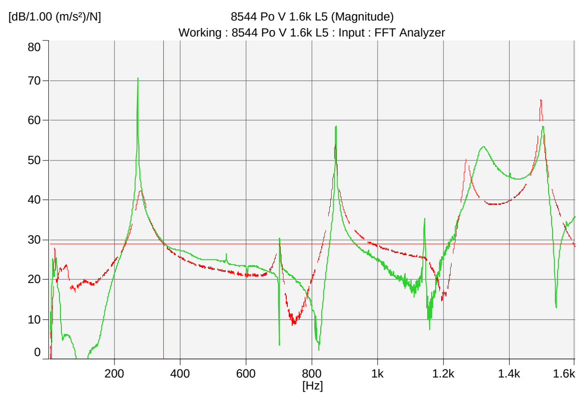

Fig. 15 Pre-LSP (green solid), post-LSP (red dashed) natural frequencies

HCF RESULTS FROM STUDY

The data of Fig. 16 clearly demonstrate the significant fatigue improvement realized with Gen IV LSP in the presence of significant LE damage. Data presented in Fig. 16 were measured at the failure location and are presented in normalized units.

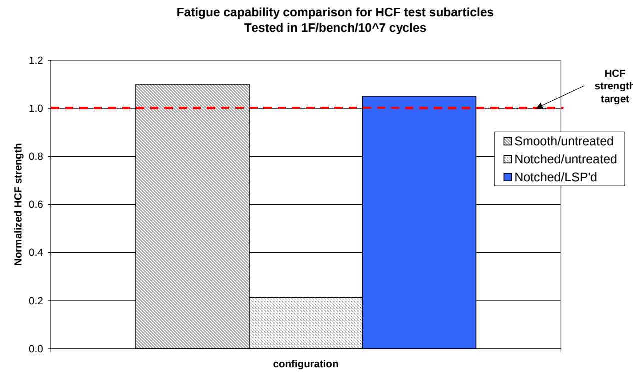

Fig. 16 HCF capability comparison of subarticle populations tested

From Fig. 16, it can be seen that the Gen IV LSP almost entirely negated the notch, restoring fatigue capability commensurate with the smooth baseline data. Relative K_f achieved for this process is almost 5. This is further significant when considered in light of the relationship of K_f with geometric K_t, per Peterson[6]:

$$q = \frac{K_f - 1}{K_t - 1} \qquad (3)$$

where the relationship of K_t and K_f are determined by the notch sensitivity factor, q. The factor q can range from q=0, or no notch effect, to q=1, or full effect i.e. the material in question is fully notch sensitive. Thus, for q=1, $K_t = K_f$ and the material "sees" the full theoretical geometric stress concentration. Given that typical forged titanium notch sensitivity at stress ratios of R=-1 is ~.8 (conservative for purposes of this discussion), the results above thus imply that the notch geometry imposed for this study produces a K_t greater than 6 and further, that the subsequent fatigue strength recovery produced by Gen IV LSP represents an equivalent K_t abatement well exceeding 5 when compared to untreated/notched specimens.

FRACTOGRAPHIC STUDIES OF LSP SPECIMENS POST-FAILURE

In order to further understand the performance of Gen IV LSP in the arresting of fatigue cracks during siren testing, fractographic analysis was conducted of several specimens of the study described here. Fig. 17 shows a typical specimen post-failure, with a fatigue crack

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presented through the surface of the blade subarticle. Following macro examination of the subarticle, the crack was opened and the fracture surface inspected both via optical and scanning electron microscopy (SEM).

Fig. 18 shows a low magnification montage with break out higher magnification views via SEM. Review of the fracture surface confirmed crack initiation at the LE notch terminus site consistent with the geometric stress concentration of the notch and with subsequent propagation through the airfoil section clearly visible at the surface of the article from macroscopic examination. The feathery appearance of the initiation site is indicative of a fatigue initiation versus a tensile initiation.

The fracture surface inside the LSP patch exhibited a rougher texture than the fracture surface outside the patch, ostensibly due to the arresting behavior of the compressive stresses in the patch. SEM views confirmed fatigue striations appearing outside the patch and the trend in striation spacing imply crack acceleration from a low growth rate inside the patch to a higher growth rate outside the patch. The SEM views also confirmed the direction of crack propagation away from the notch observed macroscopically during siren testing.

As part of the development of the Gen IV process and not part of this study, fractography of Gen IV subarticles had been compared to Gen II subarticles fatigue tested in a similar manner. This comparison indicated that Gen IV fracture features exhibit equivalent morphologies as those of the earlier Gen II process, thus further demonstrating similarity of the new process.

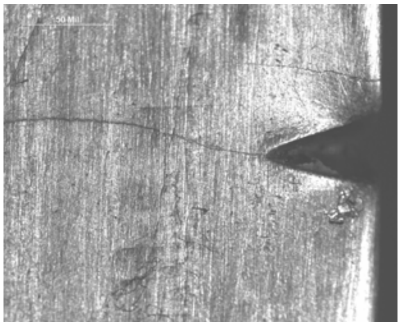

Fig. 17 Crack propagated from notch during siren testing of LSP sample

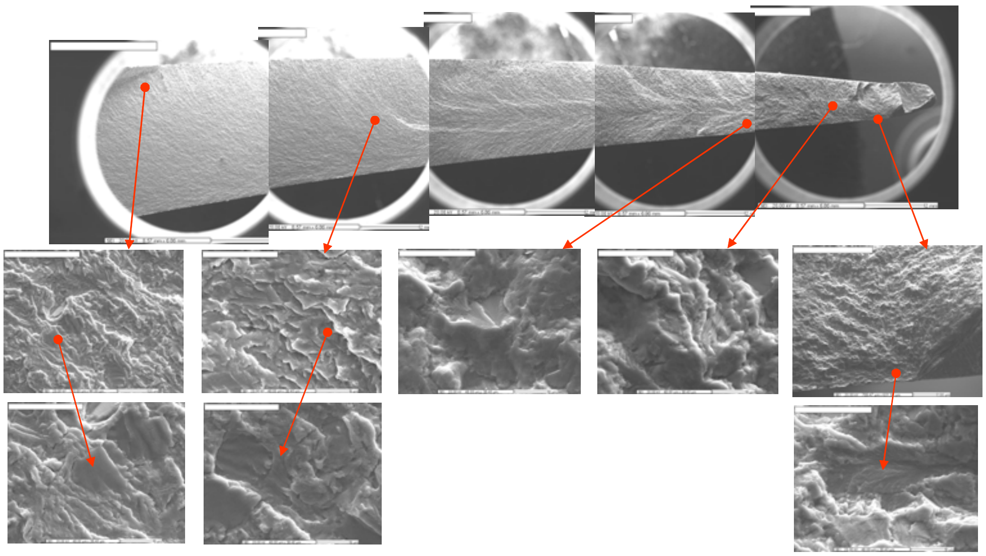

Fig. 18 Fractography of sample after HCF testing

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CONCLUSIONS

GEAE's Gen IV LSP process has demonstrated the ability to meet the technical expectations previously set by GEAE's successful Gen II process. Fan blades of Ti 6Al-4V alloy processed with Gen IV LSP demonstrated a 6x improvement in HCF capability with simulated FOD while still meeting post-LSP distortion limits. Additionally, Gen IV satisfied demanding requirements of this study in which thick section material was processed as a challenge to a low-energy LSP process. Results of this study demonstrate a process ready for production optimization.

ACKNOWLEDGEMENTS

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