Laser Peening for Improved Fatigue Strength and Lifetimeof a Wing Attachment Shear-Tie

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Abstract:
Laser peening is shown to improve fatigue strength and life in test parts simulating the Al-7050-T7451 wing attachment shear tie for an operational Navy aircraft. Fatigue tests were conducted on parts fabricated and treated in accordance with the processes in current use (ion vapor deposition (IVD) coated and shot peened) and others with laser peening added. Additional parts were prepared with a 0.25 mm deep EDM notch to simulate damage or crack initiation. Without exception, laser peening outperformed all otherwise prepared specimens by as much as10 times for the case of the notched (simulated damage) specimens. Laser peening is a deterministic, robotically applied process for which the Navy allows taking fatigue life credit.

Keywords: laser peening, fatigue life enhancement, crack growth

Introduction:
Laser peening technology has matured into a fully qualified production process that is now in routine and reliable use for a broad range of metal alloys. Deep compressive stress developed in metal surfaces extends both the fatigue life and stress corrosion cracking life of components. The qualified process and a companion finite element analysis (FEA) modeling that describes the resulting stress and strain profiles enable designers to consider the process for mitigating higher stress levels in certain life limited designs and for precision shaping and shape corrections. The technology is being applied to critical stress areas of commercial and military systems, including among others, a range of aircraft engines and structures and electric power generation turbines. A broad range of materials are in production or development, including but not limited to: Ti 6/4 (alpha and beta and BSTOA), 300M, HyTuf and Aermet 100 steels, Al 7050, and Al 2023. Enhancement to the life of components with complex geometries and welds has been demonstrated. The processing capability was extended with the introduction of transportable laser peening systems with moveable beams that now treat large systems in the field. The basic physics of laser peening, known for some 25 years [1, 2, 3], is shown in Figure 1. In our embodiment a roughly 25 J at 25 ns output beam from a Nd:glass laser is propagated onto the workpiece in which it is desired to induce residual compressive stress and/or to affect deterministic shape change. The area to be peened is covered with tape or coating material to act as an ablative layer and simultaneously as a thermal insulating layer. A thin stream of water is made to flow over the ablative layer. The laser light passes through the transparent water layer and the leading temporal edge of the laser pulse is absorbed by the ablative layer. This absorption rapidly ionizes and vaporizes more of the ablative material forming a plasma that is highly absorbing for the rest of the laser pulse. This plasma is confined by the inertia of the water layer and attains a pressure in the range of 50 kbar. The spot size for an individual laser peening impact is a square in the range of 3 mm to as much 10 mm on a side scaled so that the shock wave intensity is one (1) to two (2) times the dynamic yield strength of the material being peened. This pressure wave generated by this large footprint laser beam can propagate into the metal to a depth roughly equivalent to its width with nearly constant yielding intensity thereby plastically compressing deeply into the material. The resulting transverse expansion of the compressed material reacts within the component to generate a compressive stress field and/or strain (shape change) depending on the component's geometry and material properties. The plastic strain depth results in residual compressive stress induced to depths up to 8 mm or with lower intensity processing as shallow as desired. Precisely controlling the laser parameters controls the intensity and depth of the applied residual stress.

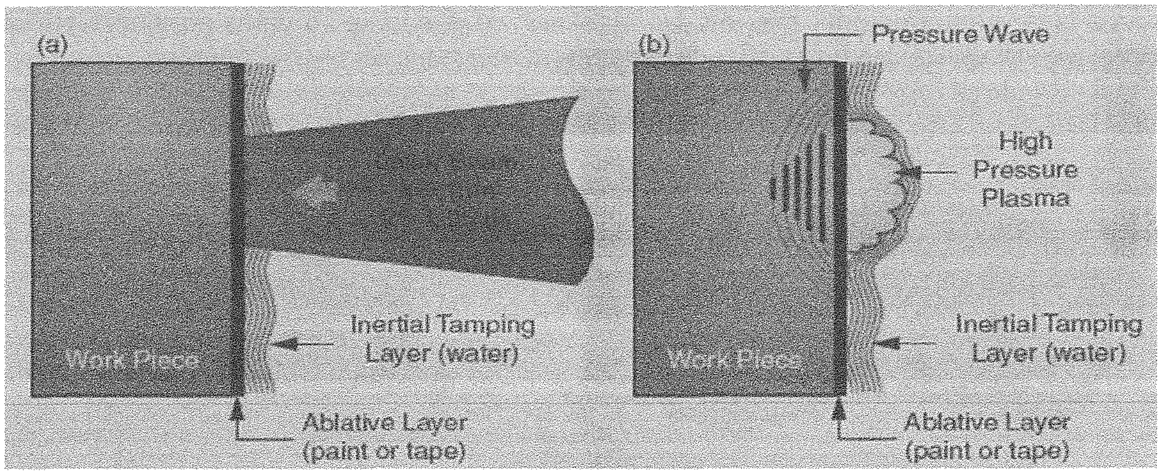

Figure 1. Laser peening concept is depicted in which ablation from a sacrificial surface creates a high pressure plasma and consequent pressure wave that yields the material and results in a deep compressive stress in the workpiece.

Thus, laser peening can be made to penetrate much more deeply than most other surface treatments such as shot peening. The penetration depth of shot peening for example is limited by the impact size and yield strength of the shot. Figure 2 shows the results of shot and laser peening Aluminum 7050 T7541. The nomenclature of 4-18-3 in the figure represents laser peening with an irradiance of 4 GW/cm^2, pulse duration of 18 ns, and 3 layers (300%) coverage. As seen in the figure, shot peening develops excellent surface stress in the range of 420 MPa and penetrates to a depth of about 0.25 mm. In contrast, laser peening produces roughly the same level of surface stress but displays a 10 times deeper zero crossing depth of stress. In actuality, the Al7050 test piece has taken on a curvature from the intense laser peening; had a much thicker and thus stiffer coupon been treated, the depth of measured compressive stress would have been closer to 5 mm suggesting the actual depth of treatment attained.
The laser peening parameters can be reduced to generate less penetrating stresses as desired; anywhere between the deep level shown to stresses closely matching shot peening. A key feature of laser peening is the highly controllable nature of the process, a feature that meets Navy requirements to allow credit to be taken for the processing.

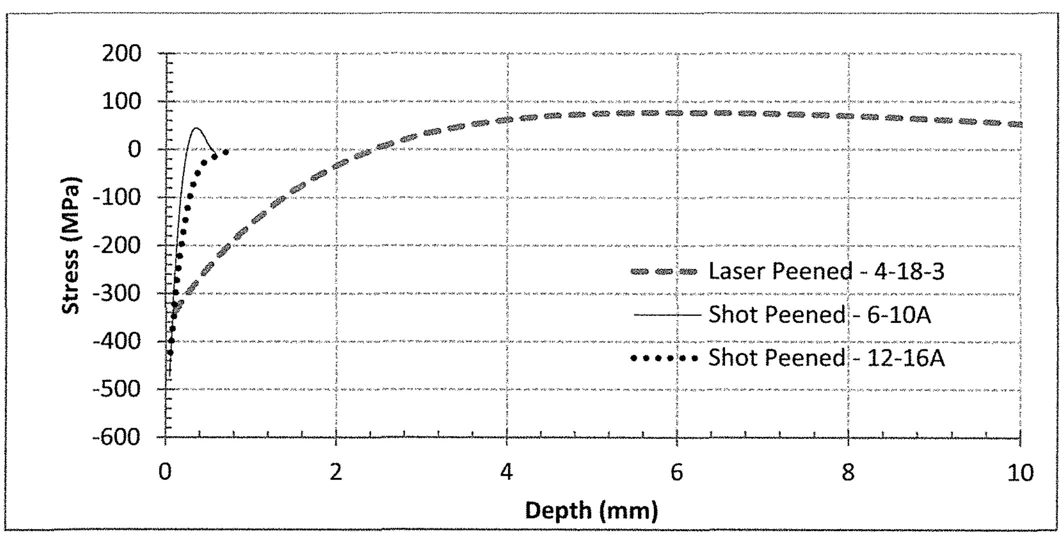

Figure 2. Laser and shot peening measured via crack-compliance/slitting show residual stress results generated in Al 7050 T7451.

The large laser beam footprint and intense pressure wave enable 10 times greater depth of compressive stress, as compared to a moderate and heavier level of shot peening.

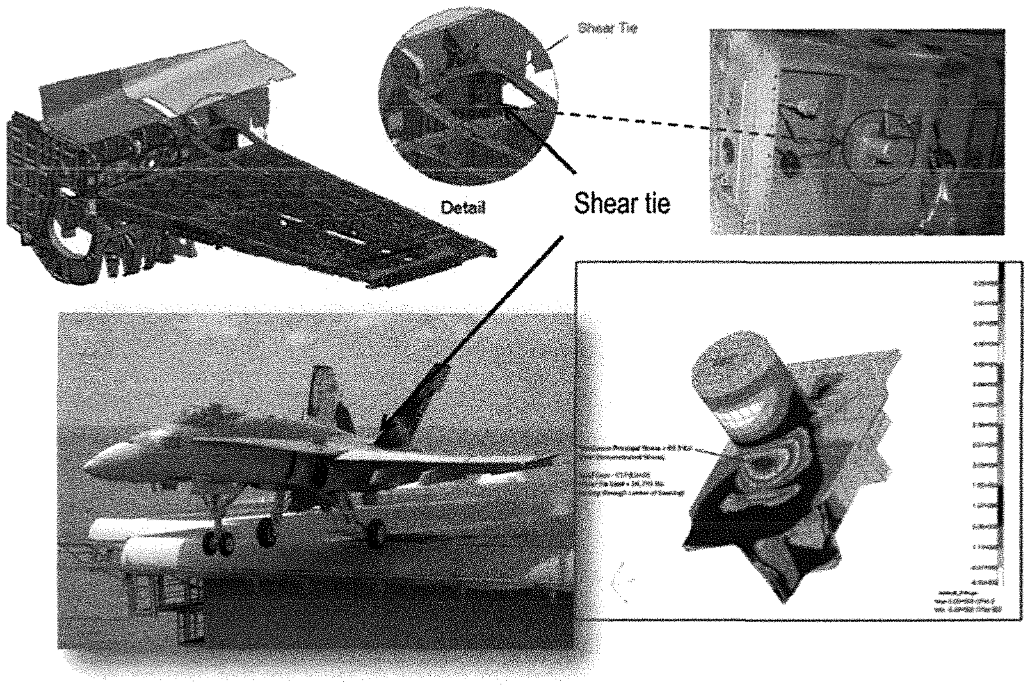

Figure 3. High stress loading of an aircraft shear tie generates a safe-life limit as the aircraft acquires extensive flight hours. Laser peening can be applied selectively to the high stress region to mitigate fatigue crack initiation and crack growth.

Aircraft application:
Structural components of US Navy aircraft are typically operated in a safe-life mode where detailed engineering, testing and analysis define an allowable lifetime. Continued operation is often desired beyond the safe-life limit. Surface treatments can extend the limit but require processing to be mechanized and traceable. Such was not the case with the F-18. The component in question, the Y508 shear tie, was fabricated with ion vapor deposition (IVD) coating and then shot peening (SP). The component and its location on the aircraft are identified in the series of photos and drawings in Figure 3. Upward lift from the wing during flight generates a shear and bending moment that puts tensile stress and thus fatigue life debit into the "hotspot" region, as identified in the false color component section in the bottom right-hand area of the figure.

Since peening and testing of full-sized aircraft was not realistic, a test specimen was designed to replicate the stress gradient generated during flight. Because the aircraft loading is axial (shear) and bending, a two-sided test specimen was designed to eliminate high-off axis loading of the fatigue test rig. Figure 4 shows the final specimen design and the stress generated (on both sides) in the "hotspot" during loading. Specimens were machined of 7050 aluminum and then treated with ion-vapor deposition (IVD) and shot peening (SP) all per the aircraft specification. Since the Navy does not allow design credit for the shot peening as was applied, some test specimens were left "as-machined," others IVD coated only, and yet others received IVD plus shot peened. For another set of specimens a laser peening pattern was designed to mitigate the tensile loading stress in the "hotspot" region. Then following IVD plus shot peening, the laser peening was applied to these specimens. This step for laser peening was intended to replicate how existing aircraft could be treated in the field for safe-life extension.

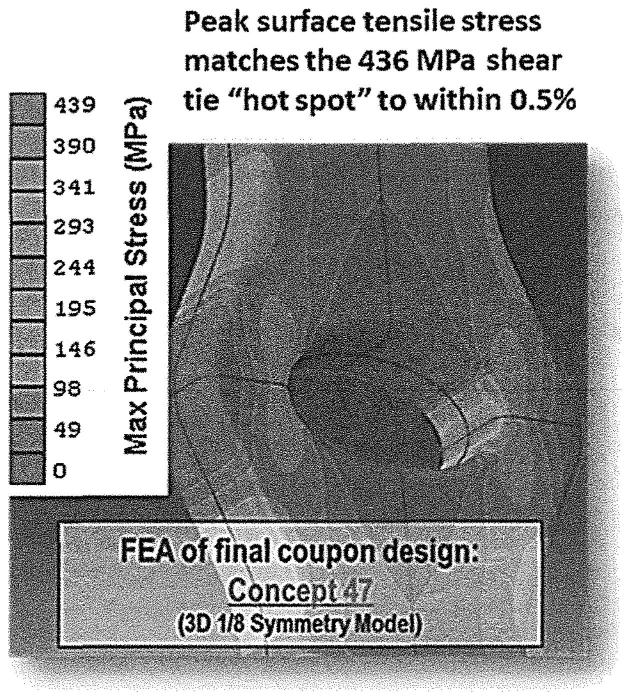

Figure 4. Under axial loading the fatigue test specimen design enables replicating the shear and bending loading of Y508 shear tie as experienced during flight operations.

Fatigue tests were completed on 40 specimens using a 500 kN MTS load frame and a Navy specified load spectrum. Each spectrum block was repeated until failure or run-out. A marker-band sequence included in the load spectrum facilitated quantitative crack growth measurements Test conditions, post-test part inspection, and crack growth analysis methods were developed and approved in collaboration with the Navy.. Laser peening (LP) was applied with 300% coverage at 4GW/cm^2 in accordance with SAE AMS 2546 and shown to generate compressive residual stresses to 3.75 mm depth. This is in contrast to depths of only0.4 mm achieved with the current IVD and shot peening (SP) process alone. This deep residual stress explains the fatigue life improvement provided by LP and agrees with the large database generated to support current commercial and defense LP applications for improving fatigue life in aircraft and aerospace components.

Quantitative fractography was carried out on 22 primary cracks from 15 different specimens and used to evaluate the performance of the different surface treatment conditions. These analyses were done primarily through reconstruction of crack growth curves after specimen fracture. This was facilitated by use of a fatigue spectrum that was slightly modified to include a marker sequence. The fatigue marker sequence produced one marker band per each fatigue spectrum block.

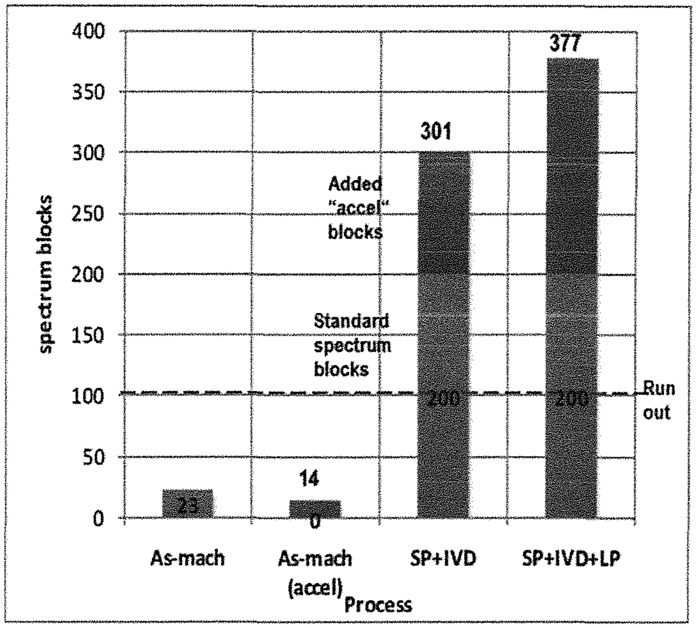

Figure 5. Direct comparison of shot peened (SP) to shot plus laser peened (SP+LP) test specimens.

The marker band analyses reliably reconstructed crack growth to depths < 0.05 mm (0.002 inch) and occasionally < 0.00025 mm). Growth rates are found to correlate well with the expectations from the measured residual stress field. For example, fractography reveals that crack growth behavior for SP and SP+LP treatments is similar for crack depths approaching 0.25 mm. Beyond this, however, the SP+LP treatment dominates, delivering crack growth rates 10 to 20 times slower than SP, at a range of crack depths from 0.75 to 1.75 mm. Figure 5 shows fatigue test results. Laser peened specimens showed a 25% lifetime increase. However, no cracking initiated in the laser peened "hotspot" area, indicating that the lifetime improvement for laser peening is more realistically in the 200% to 400% range. Further testing is being done with extended laser peening to retard cracking from initiating in the areas not representative of the Y508. These results indicate that the SP+LP treatment can produce life improvements over the SP treatment by at least a factor of two to four; moreover, >10 times improvement is readily attainable relative to the "as-machined" baseline condition. Figure 6 shows dramatically beneficial results for laser peening in the case of a 0.5 mm deep surface flaw induced by a plunge EDM. In the case of surface flaws or damage during operation, the benefit of the deep residual stress of laser peening (LP) is especially evident. For initial crack depth of ~0.25 mm the benefit is in the range of 10 times.

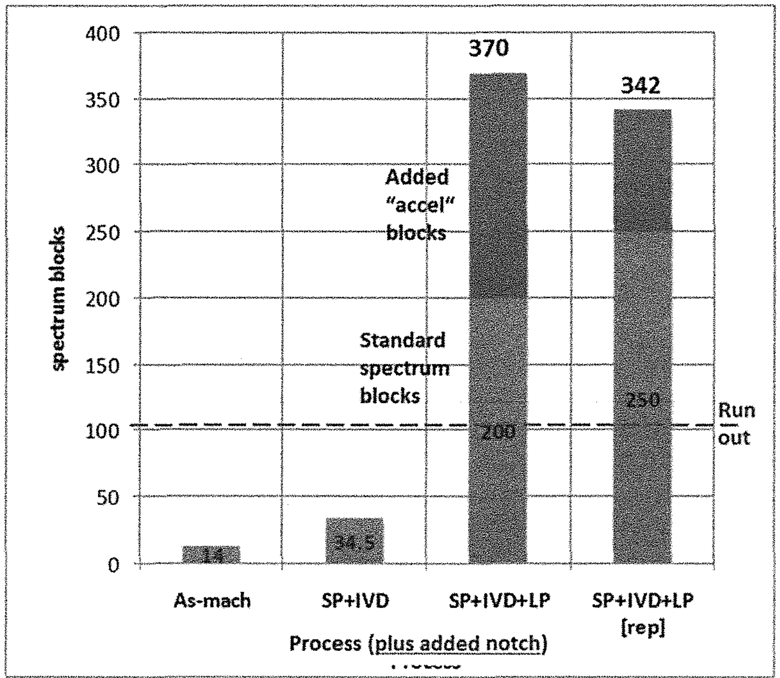

Figure 6. The benefit of laser peening dramatically increases in the presence of a 0.25 mm deep surface flaw.

Discussion and Conclusions:
Laser peening is shown in this example to be an excellent solution to aircraft fatigue problems and in particular to safe-life extension. As an FAA qualified process, it also has the advantage that it can be implemented on-aircraft as in a current application to mitigate fatigue cracking on F-22 fighters [4]. Thus, it is ideally suited for many aging aircraft applications, such as the wing attachment shear tie reported here.

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