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Laser Peening to Improve Fatigue Strength and Lifetime of Critical Components*

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Abstract

Fatigue failure is typically driven by component geometric requirements that result in local areas of high tensile loading stress. Within this paper we discuss the deep protective stress generated by laser peening and show examples of using a newly developed finite element predictive strain and stress tool that accurately models laser peening. The analysis tool and robust process enable the accurate engineering of local compressive stress into critical areas of diverse/all(?) ferrous and non-ferrous materials in a well-defined manner that significantly improves fatigue life and strength. This capability opens the potential for advanced designs with increased performance, enhanced reliability and reduced system weight.

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Keywords: engineered stress, laser peening, finite element analysis, fatigue, finite elemente analysis (FEA)

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1. Laser Peening - modeling and application

The laser peening process has the ability to generate plastic deformation, uniquely deep and with spot by spot placement thus enabling components to achieve equally deep levels of residual compressive stress. This deep stress greatly improves resistance to fatigue and stress corrosion cracking failures. The processing is done with only a few intense impacts to each local surface area and thus results in low cold work and corresponding retention of residual stress in long term fatigue applications and under elevated temperatures. A most recent advance has been in the development of finite element modeling that enables the peening to be virtually designed into components allowing iterative analysis of the optimum placement of desired compressive stress and management of resulting tensile stress. A recently-developed finite element analysis (FEA) code model of the process allows evaluation of stress profiles and strains of components prior to and following laser peening. Adding into the analysis the operational loads, the reduction in peak tensile loading can then be assessed to estimate lifetime improvements, reduce design cross section and component mass and to optimize the overall peening. We describe the laser peening technology, our finite element modeling and provide examples of applications leading to improved design and performance.

2. Laser Peening Technology

Laser peening is a highly controlled process that creates plastic deformation to depths multi-millimeters deep into a metal surface. The process is used to generate desired compressive stress and controlled component strain. Deterministic control, shot-by-shot for each laser pulse enables very specific stress or strain to be generated. Figure 1 shows the basic concept for the laser peening. A thin layer of de-ionized water is flowed over a surface to be treated providing a tamping layer for the plasma formed. A high energy laser beam, typically of 20 Joule energy, enables irradiances in the range of 2 GW/cm^2 to 10 GW/cm^2 over large spot sizes of 3 mm squares to 1 cm square. The laser light passes through the water and forms a plasma in nanosecond time on a thin layer of aluminum tape adhered to the metal. Absorbing additional laser light and trapped by the inertia of the water, the plasma pressure builds to 10-30kbar pressure in nanosecond time. By adjusting the footprint size of the laser beam, done as needed robotically in real time, the irradiance of the beam is set to create a plasma pressure wave that is one to two times the dynamic yield strength of the material being treated. The large centimeter scale of the laser beam footprint results in a planer pressure wave that propagates multi-millimeters deep into a metal surface before rarefying and losing it ability to plastically react with the material. A key benefit of high energy laser peening is the generation of this deepest level of plastic strain and thus the resulting deep compressive residual stress.

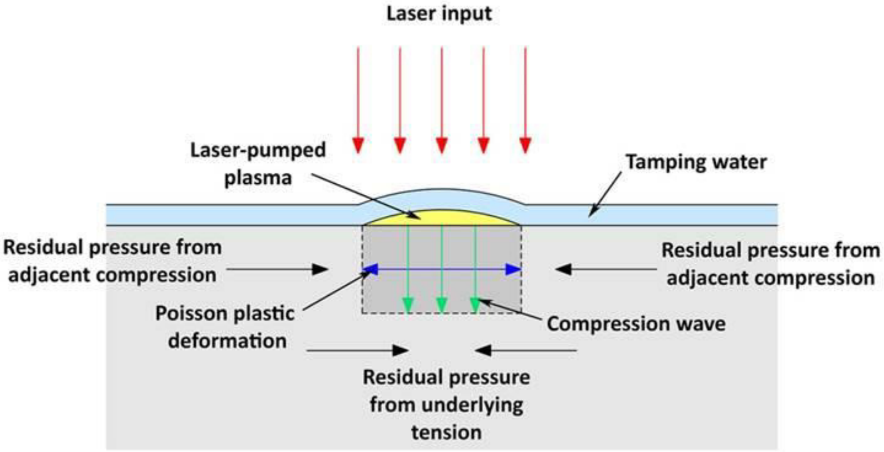

Figure 1. Laser peening concept and response of material compressing normal to the surface and generating transverse stress and strain response

As the material is compressed normal to the surface, it attempts to conserve its volume and expands in the transverse directions. Depending on the geometric stiffness (moments of inertia) of the component and the area being peened, a combination of stress and strain results associated with the peened area. Stiff components (larger moment of inertia) will mostly hold stress and will strain by only small amounts whereas thin components will show significant strain which can result in much less residual stress.

Because of the large footprint of each shot, the laser peening process has the ability to generate very deep levels of plastic deformation, uniquely deep, and thus enable components to achieve equally deep levels of residual compressive stress. This deep stress greatly improves resistance to fatigue and stress corrosion cracking failures. The processing is done with only a few intense impacts to a surface area and thus results in low cold work and corresponding retention of residual stress in long term fatigue applications and under elevated temperatures. Figure 2 shows residual stress generated in 7050 T7451 aluminium and contrasts the stress of 4 mm depth from laser peening against a typical 0.25 mm depth for shot peening.

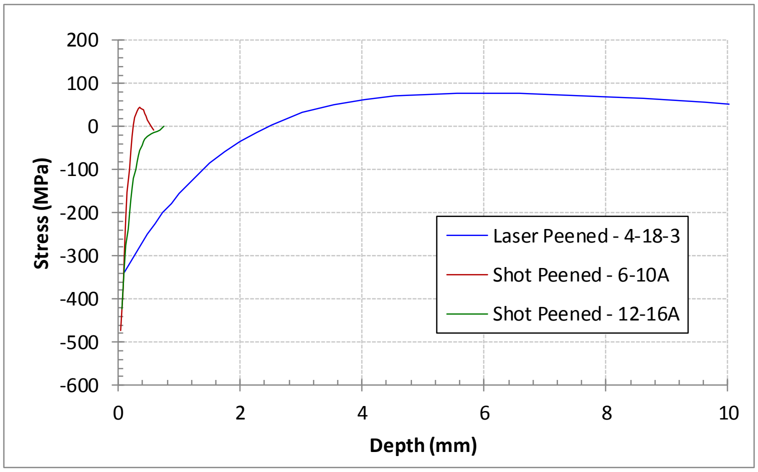

Figure 2. Laser peening of 7050 T7451 aluminium that is approximately 10 times deeper that achieved with shot peening

In the laser peening process every laser pulse is precisely controlled with respect to pulse energy, pulse duration, spot size and spot position and thus the peening response is also highly controlled. The process is FAA and EASA certified. Because of this deterministic ability to generate local stress and strain, the process can be well predicted by finite element elastic/plastic analysis to predict and then apply specific patterns and peening parameters and thus generate desired compressive stress for fatigue enhancement or controlled strain for component shaping. Figure 3 shows results obtained in Ti6/4 where the nomenclature in the graph key represents laser peening process parameters; for example 2-18-2 represents 2 GW/cm^2 laser beam irradiance, 18 nanoseconds laser pulse duration and 2 layer of laser peening coverage. The figure shows residual stress profiles for additional irradiances ranging from 2 GW/cm^2 to 10 GW/cm^2 and additional coverages which demonstrates how the laser peening can be precisely adjusted to control the generation of stress as desired. The shallower stress generated by the 1 mm square smaller spot size, where the laser energy is intentionally reduced, emphasizes the benefit of the much larger 3 mm to 1 cm spot sizes used in our high energy process.

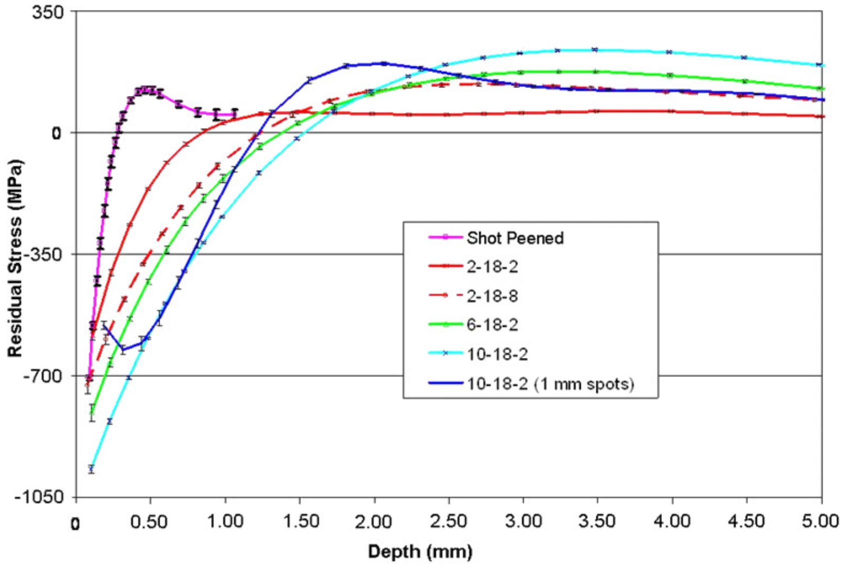

Figure 3. Laser peening residual stress vs. depth as generated in Ti6/4. Laser irradiances ranging from 2 GW/cm^2 to 10 GW/cm^2 show the ability to control depth and intensity of stress by adjusting laser parameters.

Recent development of a finite element analysis (FEA) code model of the process allows evaluation of stress profiles and strains of components prior to and following laser peening. Adding component operational loads into the analysis, the effective reduction in peak tensile loading can then be assessed to estimate a number of available improvements including lifetime and fatigue strength improvement, potential to reduce design cross section and component mass and ability to optimize the overall peening and thus fatigue performance.

3. Finite element based model of laser peening

Laser peening is a highly deterministic process applied in a spot by spot manner that thus lends itself to finite element analysis modelling and prediction of stress and strain. The process is applied via placement of individual spots of chosen irradiance, pulse duration and number of layers of coverage. We have developed a finite element model of the laser peening process that uses an input package to insert peening conditions into the ABAQUS material analysis software package which then generates plastic deformation and predicts the resulting stress and strain generated in a component being laser peened. The model is normalized for each specific material of interest by direct measurement of the strain response to laser peening of test blocks of the specific material. Our standard approach for determining how to achieve the best fatigue or shaping performance for a laser peening application is to 1) generate a solid model of the component of interest, 2) obtain mechanical and fabrication stress and strain loading information and 3) virtually apply laser peening with individual spot granularity and 4) produce the resulting stress and strain output. This process can then be easily and quickly iterated so as to virtually generate an "optimum" peening pattern and coverage that will provide the best performance. For fatigue life/strength applications the code output can be analysed in a lifetime assessment code such as AFGRO and trade of between optimum performance for crack initiation and/or crack growth rate. For shape generation or shape correction applications the code output directly provides the predicted shape which can be directly compared to desired shape.

Figure 4 in a sequence of specimen drawings, illustrates the Laser Peening FE analysis approach. Figure 5 summarizes the results quantitatively using "line-outs" of the stress profiles through the notch centre. On the far left of Figure 4 is an example test specimen with a double notch. The drawing second from left shows the specimen under axial loading and the drawing fourth from the left shows in cross section that this load generated a peak tensile stress of 180 ksi (1260 MPa) at the notch centre. Under cyclic loading the specimen would crack at this notch and fail after a relatively short number of cycles. Using the Laser Peening FE analysis to treat the notch area, the specimen third from the left shows a compressive stress of 130 ksi (910 MPa) can be generated when a designed laser peening is applied; the laser peening pattern is shown schematically by the squares in the notch of the first drawing. When we superimpose this "engineered" laser peening stress on to the loading stress we obtain the stress profile shown by the drawing at the far right where the peak stress has been significantly reduced. Referring quantitatively to Figure 5, we see that the superposition of stresses results in a reduction in peak stress of 28% but

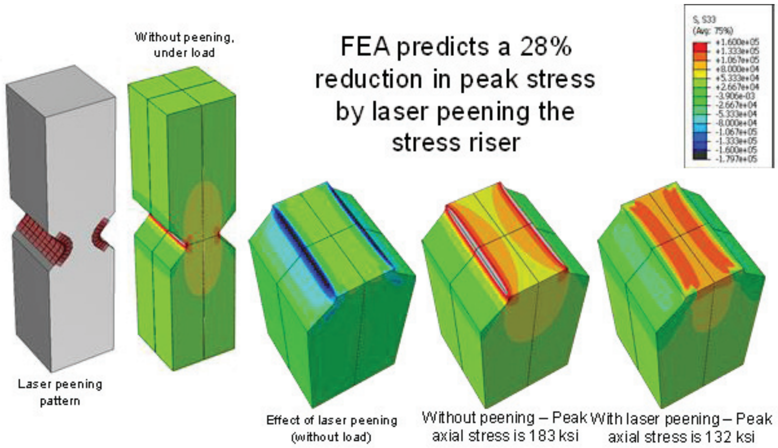

Figure 4. The stress loading profile of a notched tensile bar rises to a stress of 1281 MPa (183 ksi) under loading. Laser peening applied to the high stress area of the notch reduces the peak stress to 924 MPa (132 ksi) enabling significantly longer fatigue lifetime.

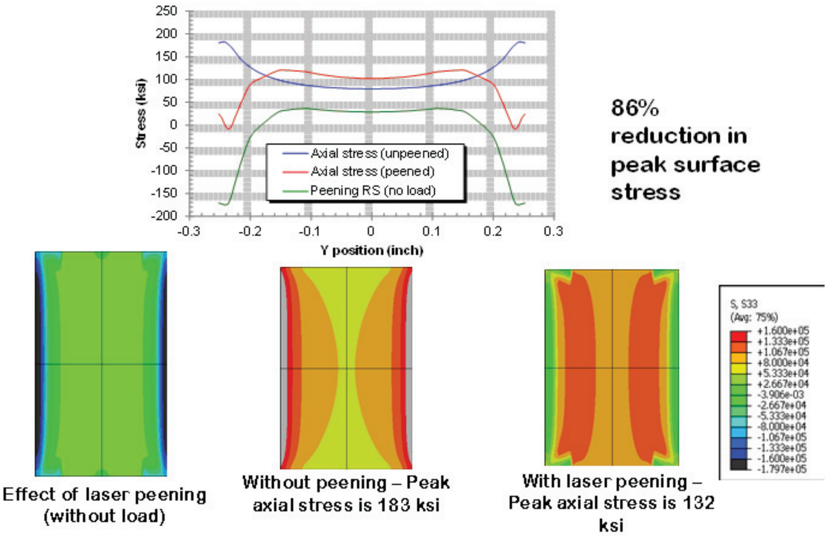

Figure 5. Laser peening reduces the peak stress in this test specimen by 28% but even more significantly it reduces the surface stress, where cracking generally initiates, by 86%.

even more significantly a reduction in the surface stress of the notch of 86%. The compressive stress generated by the laser peening did result in the generation of a compensating tensile stress but that stress has appeared safely in the centre of the specimen where the loading tensile stress is much lower as shown in the Figure 4 drawing on the far right. Basically the laser peening has allowed us to pre-bias the area of known high stress with a pre-determined compressive stress and move the loading to be more uniformly spread across the entire cross-section.

Figure 6 is an SN (stress vs. fatigue cycles) curve for Al6061 and illustrates the potential benefit of reduction of loading stress. If we consider a tensile stress load reduction of 28% as discussed above, we see for example that the load stress of 90 MPa reduces to 65 MPa and the shot peened component lifetime would increase from 20,000 cycles to approximately 120,000 cycles. The laser peened component lifetime would increase from 120,000 cycles to well over 1 million cycles. For an application intended to reduce the weight of a component that meets lifetime requirements, the 28% reduction in peak loading stress translates directly into an available 28% reduction in cross section and thus a reduction in component mass.

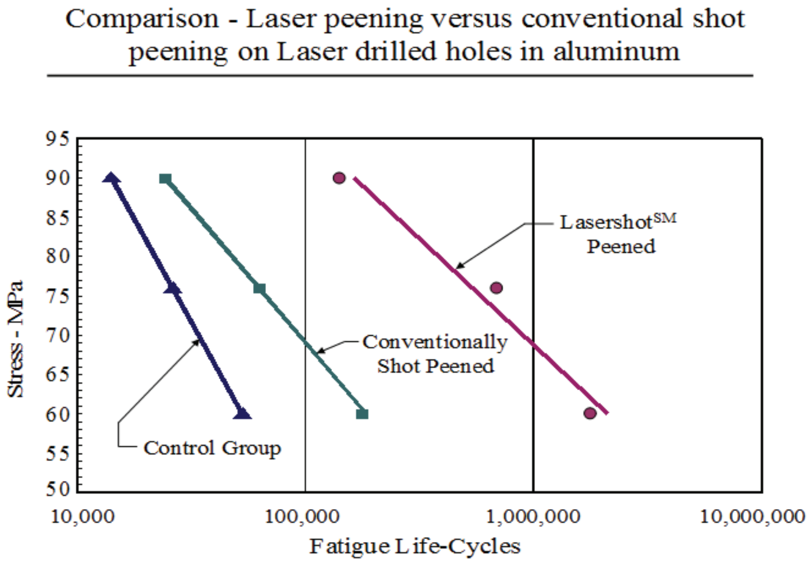

Figure 6. Residual stress in high stress areas of components can be used to increase fatigue lifetime or fatigue strength.

4. Laser peening analysis and implementation: An advanced tool for application to fatigue design

The power of the laser peening modelling is that work can be done analytically and evaluated rapidly in structure designs with complex geometry and mechanical and thermal loadings. Applications of the model have established confidence that the laser peening implementation will replicate the analysis quite faithfully in the actual structures. Thus fatigue issues can be evaluated and solved at the design level before they become fatigue problems in fielded hardware. Using the FE analysis fatigue performance can be optimized more rapidly and with much reduced level of mechanical testing. This process of optimizing the laser peening and thus the fatigue performance by finite element analysis followed by streamlined implementation and test verification has enabled identified problems to rapidly move to solution and implementation. The concept is also enabling the laser peening process to be used more extensively in design rather than waiting to fix systems that fail in the field.

An example of where laser peening can be applied to an existing system component is the high stress area of the Y508 shear tie on the F-18 aircraft. Figure 7 shows the aircraft and Figure 8 indicates where the shear tie is located at the fuselage to wing connection. Figure 9 shows the high stress tensile loading developed during cyclic wing uplift and indicates where the FE analysis guided the design of a spot-by-spot peening pattern that can mitigate the loading stress and extend fatigue lifetime. Figure 10 shows residual stress values for various conditions of the Al7050 T7451 material used for the shear tie Compressive stresses were developed for input to the analysis in test blocks under various treatment conditions: by ion vapor deposition (IVD), shot peening (SP) and laser peening (LP). The IVD process is applied to aircraft structure for corrosion resistance during manufacturing. The shot peening (SP) was routinely applied to the aircraft but because it was not a highly controlled process credit could not be taken for the safe-life analysis used for the aircraft. The laser peening is added to the IVD and SP processes because in the field the laser peening would be added to existing aircraft where the IVD and SP have been already applied. In the modelling code elastic strain as measured by treatment in the blocks is input to the analysis as strain and the code generates the response of the shear tie area in stress and strain including the compressive and resulting tensile stresses.

Figure 7. F-18 aircraft fuselage develops a high stress at a fuselage structure called the Y508 shear tie

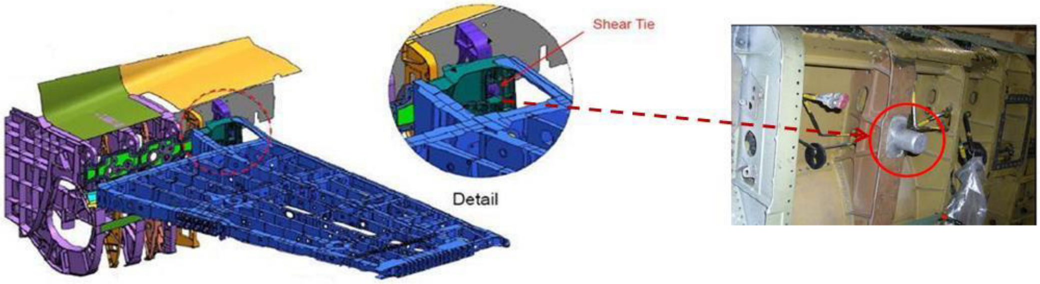

Figure 8. Uplift of the wing and relaxation of the wing generates a cyclic tensile loading to the Y508 shear tie

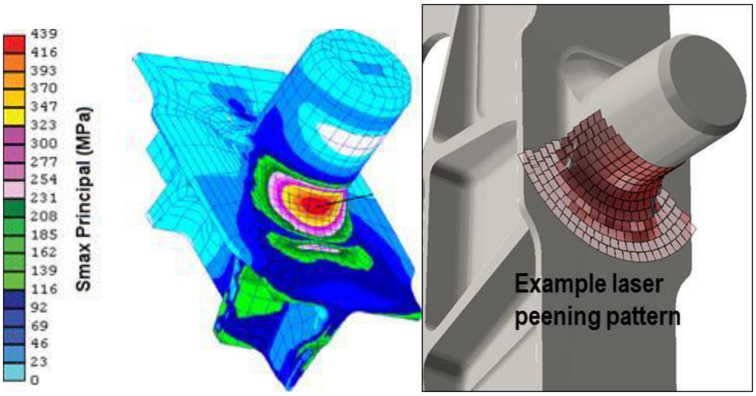

Figure 9. Tensile loading of the shear tie can be mitigated by compressive prestress generated by laser peening. The spot-by-spot pattern was generated with stress profile guidance from the laser peening FEA code

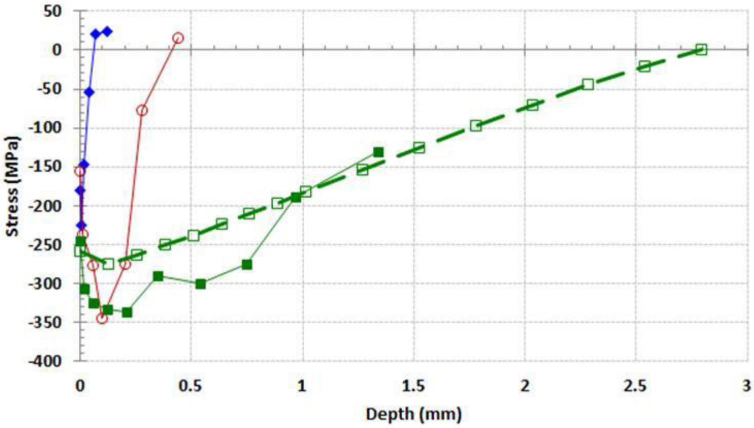

Figure 10. Laser peening (LP) generates deeper compressive stress than ion vapor deposition (IVD - added for corrosion protection), or shot peening (SP) and thus provides the best fatigue protection. Because the LP processing is intended for existing aircraft, it is added on top of the SP and IVD treatments which are already present.

With data provided to us for the stress loading of the shear tie we input a solid model of the structure into the FEA code and used the code to iterate design concepts for a test specimen. It was desired that the test specimen develop nearly identical stress profile in a fatigue test and that the loading in the test rig be symmetrically balanced so as not to excessively off-centre load the test rig bearings. Figure 11 shows the stress gradient developed in the shear tie and the equivalent stress developed in the 47th iteration of test specimen design evaluated by the FEA code. Figure 12 shows the final test specimen design which developed the appropriate axial and bending load stresses in a two-sided manner enabling symmetric loading in the test rig.

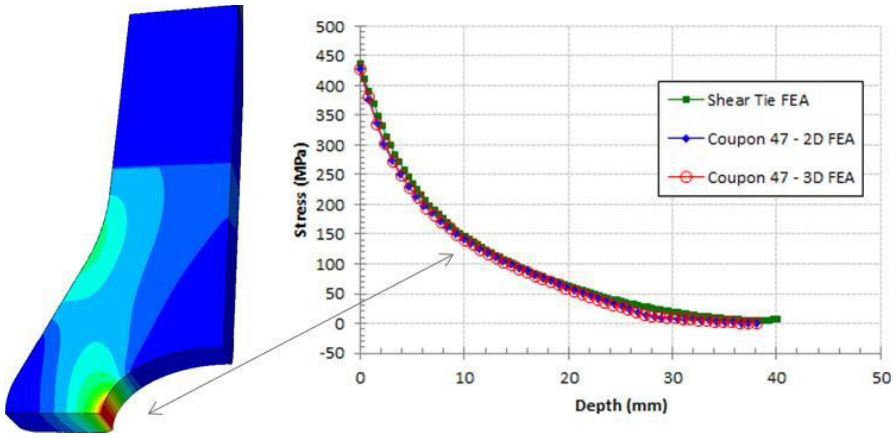

Figure 11. The FEA code was used to analyse the stress intensity and gradient developed by operational loading in the Y508 shear tie and to develop a fatigue test specimen that well replicated the stress profile.

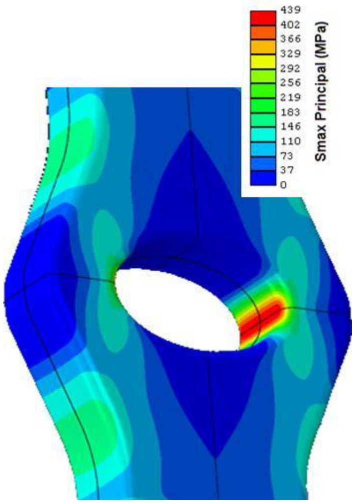

Figure 12. Fatigue test specimen design showing residual stress profile generated by the 47th iteration of the FEA code. This axial pull specimen generated bending and axial loading on each of two symmetric sides.

With a representative design in hand, fatigue test specimens were manufactured and a series of tests was run. A fatigue test load spectrum was provided by US Navy NAVAIR and specimens run in the condition of as-machined, shot peened plus ion vapor deposition treatment (SP + IVD) and shot peened plus ion vapour deposition treatment plus laser peening (SP + IVD + LP) conditions. The SP + IVD condition is that for as-built aircraft that have been in routine operation. Figure 13 shows one of the test result sets comparing the three surface-treatment conditions in the case where a small EDM plunge notch of 250 micron diameter by 125 micron depth is cut to simulate an initial flaw. The figure clearly shows the benefit of the deep protective compressive stress where the laser peening provides a more than 10 time lifetimes improvement over the as-built condition.

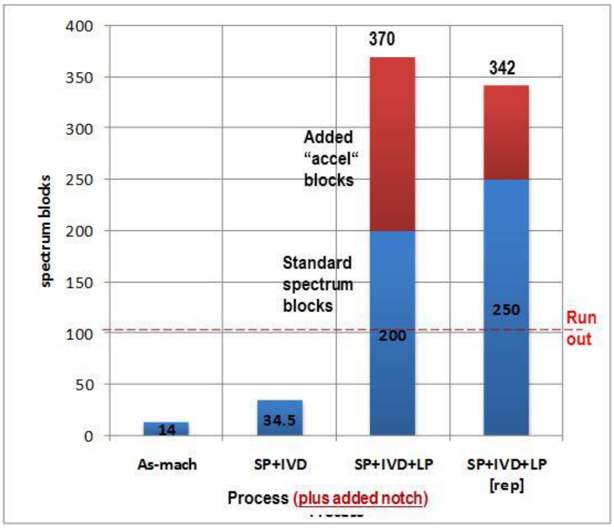

Figure 13. Test results comparing the three starting conditions in the case where a small EDM plunge notch of 250μm diameter by 125 μm depth is cut to simulate an initial flaw.

Additional test results, shown in Figure 14 show the benefit of laser peening for different initial crack sizes. For all crack sizes from small 50 µm size to a significant 1.25 mm size the laser peening significantly reduced the crack growth rate extending the lifetime of the component.

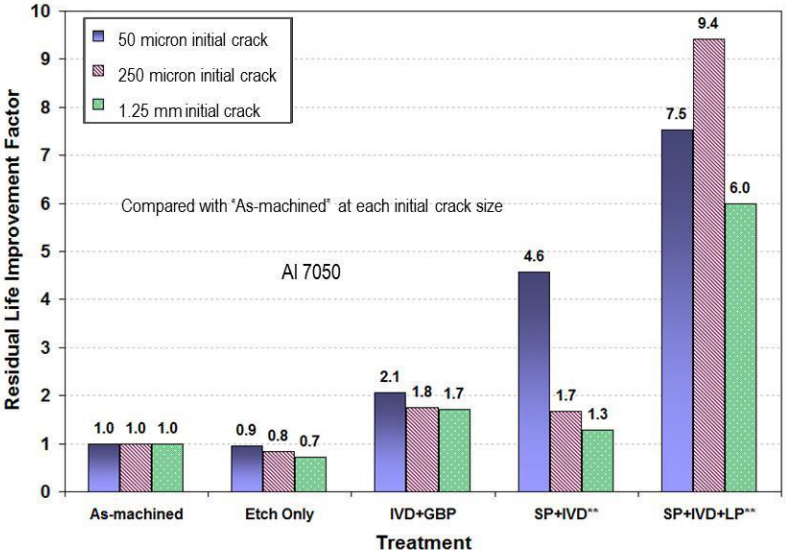

Figure 14 The fatigue benefit of laser peening for different initial crack sizes 50 µm to a significant 1.25 mm size show that laser peening significantly reduces the crack growth extending the lifetime of the component.

5. Summary

Laser peening technology provides a significant tool for advanced component and structure design enabling the designer to engineer residual compress stress into key fatigue prone areas. Recent development of a finite element analysis (FEA) code accurately predicts strain and thus stress generated by the laser peening. The use of the code enables the accurate engineering of deep residual stress into complex component designs. The FEA code and laser peening technology have been employed to improve the fatigue performance of operating systems.

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