EFFECTS OF LASER PEENING ON FATIGUE LIFE IN AN ARRESTMENT HOOK SHANK APPLICATION FOR NAVAL AIRCRAFT*

M. J. Leap[1], J. Rankin[2], J. Harrison[3], L. Hackel[2], J. Nemeth[4], and J. Candela[1]

[1] Naval Air Warfare Center – Aircraft Division, Paxutent River, Maryland USA
[2] Metal Improvement Corporation, Livermore, California USA
[3]Metal Improvement Corporation, Wellington, Kansas USA
[4]Concurrent Technologies, Johnstown, Pennsylvania USA

Abstract
Laser peening is evaluated relative to and in combination with other means of improving fatigue resistance in a particularly severe arrestment hook shank application for a carrier-based Naval aircraft. A large-scale test specimen was designed and manufactured from Hy-Tuf steel to geometrically simulate conditions in the arrestment hook shank, and fatigue tests were conducted on peened specimens under conditions of spectrum loading that simulate aircraft arrestments. Laser peening substantially increases the resistance to crack initiation relative to conventional shot peening. A change to a higher-strength steel, Ferrium S53, significantly increases the crack initiation life of both conventionally shot peened and laser peened specimens, with the latter exhibiting the highest levels of crack initiation life for all conditions evaluated in this test program. Proof loading at levels above the design limit load, conducted before the peening operation, substantially increases the crack initiation life of conventionally shot peened specimens. In contrast, proof loading does not provide additional improvements in the fatigue life of laser peened specimens since the depth of plasticity due to proof loading is similar in magnitude to the depth or residual compressive stress introduced by laser peening. Finally, limited test results suggest that repeated laser peening over the life of a component may maximize or even extend crack initiation life; however, a significant amount of testing would be required to determine the processing parameters that maximize the efficacy of this approach to extending fatigue life.

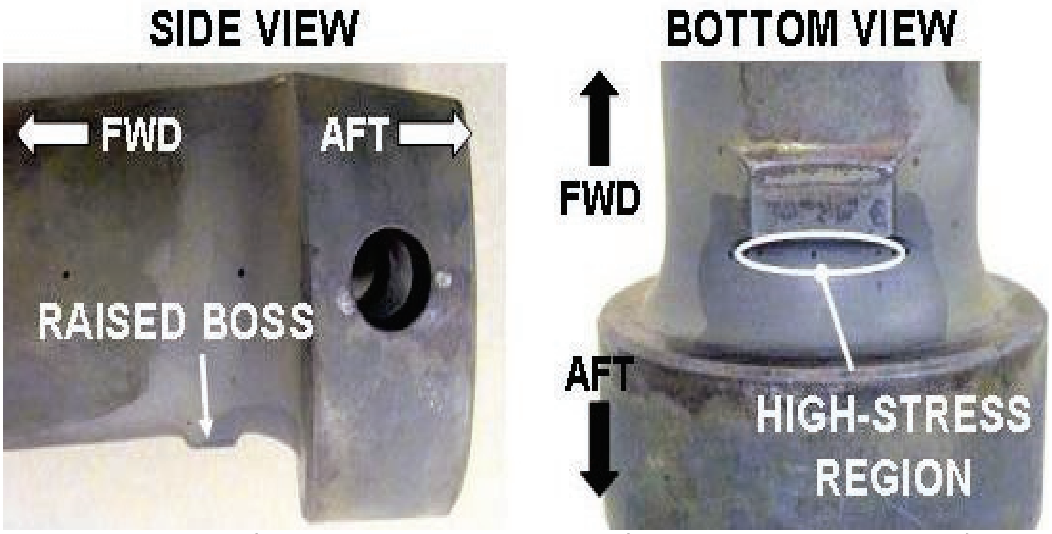

Figure 1. End of the arrestment hook shank from a Naval trainer aircraft.

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Introduction

The arrestment hook shank on carrier-based Naval aircraft is a critical component which requires the use of high-strength steel to withstand substantial fatigue loading. Recent in-service inspections revealed fatigue cracks at lives well below the design service life in arrestment hook shanks for a Naval trainer aircraft. The arrestment hook shank is manufactured from Hy-Tuf steel and conventionally shot peened as part of component processing. Crack initiation in the arrestment hook shanks occurs in a fillet on the aft side of a raised boss located on the underside of the component, and the surface trace of the crack extends along the circumferential high-stress region of the fillet, Figure 1.

Residual stress relaxation during fatigue loading is a phenomenon that typically has been associated with the accumulation of plastic deformation resulting from overloads and/or fatigue loading, sometimes in combination with thermal effects. However, the relaxation of residual stresses in the arrestment hook shank appears to result from a significant difference in the depth of compressive residual stress and the depth of plasticity resulting from applied loading.

Laser peening is an alternative process with the potential to substantially improve fatigue life in this severe arrestment hook shank application. In comparison to conventional shot peening, which produces a depth of peening on the order of 0.20-0.30 mm, laser peening can introduce compressive residual stresses much deeper (>2 mm) into a component. An illustrative example of the effects of laser peening is shown in Figure 2, where the distribution of compressive residual stress in a Hy-Tuf steel block is shown in relation to the analytical distribution of applied stress in an arrestment hook shank loaded to design limit load. The effective stresses are much lower and the distribution of effective stress is much shallower and more uniform relative to the effective stress distribution associated with conventional shot peening. As shown by this example, laser peening will improve fatigue life by suppressing plastic deformation to the greatest extent possible below the fillet surface in the arrestment hook shank.

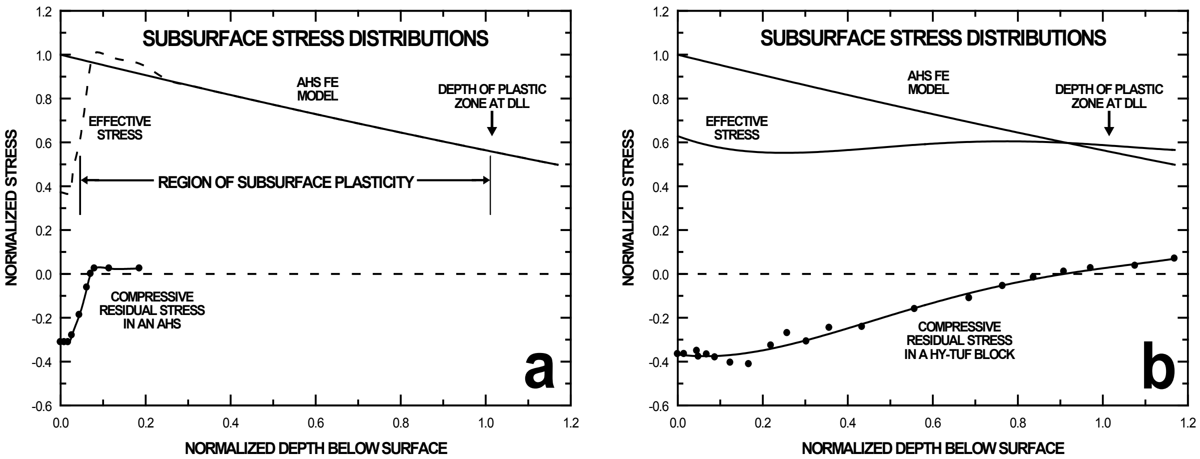

Figure 2. The analytical distribution of applied notch stress in an arrestment hook shank (AHS) is shown in relation to the distribution of compressive residual stress resulting from (a) conventional shot peening in an AHS and (b) laser peening in a Hy-Tuf steel block. Effective stress is calculated as the difference between the applied and residual stress values in each figure.

Fatigue Specimen Design & Validation

A major objective of the test program was to develop a fatigue test specimen that accurately reflects conditions in the high-stress region of the arrestment hook shank (AHS). A specimen design that satisfies these constraints is shown in Figure 3. The specimen, which is designed to interface with a conventional load frame, contains a central notch with a dimensionless notch depth of 0.5. A raised boss is positioned in the center of the flat-bottom notch to simulate the geometric feature in the AHS, Figure 1. Large radii are machined along the edge contours of the notch to suppress corner cracking in the specimen during fatigue testing.

Materials and Processing

The strain survey specimens and a majority of fatigue specimens were manufactured from Hy-Tuf steel procured in accordance with AMS 6425 [1]. Eight specimens also were manufactured from Ferrium S53™ steel in accordance with AMS 5922 [2].[1] Ferrium S53 steel was supplied by QuesTek Innovations LLC.

A majority of the specimens were tested in either the conventionally shot peened (CP) or laser peened (LP) conditions. Conventional shot peening was conducted in accordance with Boeing PS 14023 6 [3] with 230H shot to an intensity of 6 to10A with 100% coverage. Laser peening was performed by Metal Improvement Corporation in accordance with AMS 2546 [4]. LP specimens were subjected to three layers of peening (300% coverage) with an irradiance of 10 GW/cm^2, a laser pulse width of 18 ns, and a 3 x 3 mm spot size with an overlap of □3% to ensure continuity of peening coverage. LP specimens were conventionally overpeened to simulate the type of processing that would be expected during manufacturing and rework/repair activities on a laser peened AHS.

Fatigue Test Program

Fatigue specimens were subjected to a loading spectrum that simulates the time history of arrestments on an aircraft. Simulated arrestments in the loading spectrum are characterized by several variable amplitude cycles superimposed on a single loading event, and each simulated arrestment begins and ends at zero load. Crack initiation life is the fatigue parameter relevant to arrestment hook shanks, and all fatigue data presented in this investigation represent crack initiation life.

Several subsets of specimens represent different tests conducted as part of this investigation:

Baseline fatigue tests on sets of unpeened, CP, and LP Hy-Tuf steel specimens to evaluate the efficacy of laser peening on the potential to improve fatigue life in the AHS application.

- Additional tests on CP and LP specimens of Ferrium S53 steel to provide an indication of the effects of material strength on fatigue life enhancement.
- Other experiments were conducted on smaller sets of specimens remaining after the completion of the baseline testing reported in this paper.

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[1]Ferrium S53 is a registered trademark of QuesTek Innovations LLC.

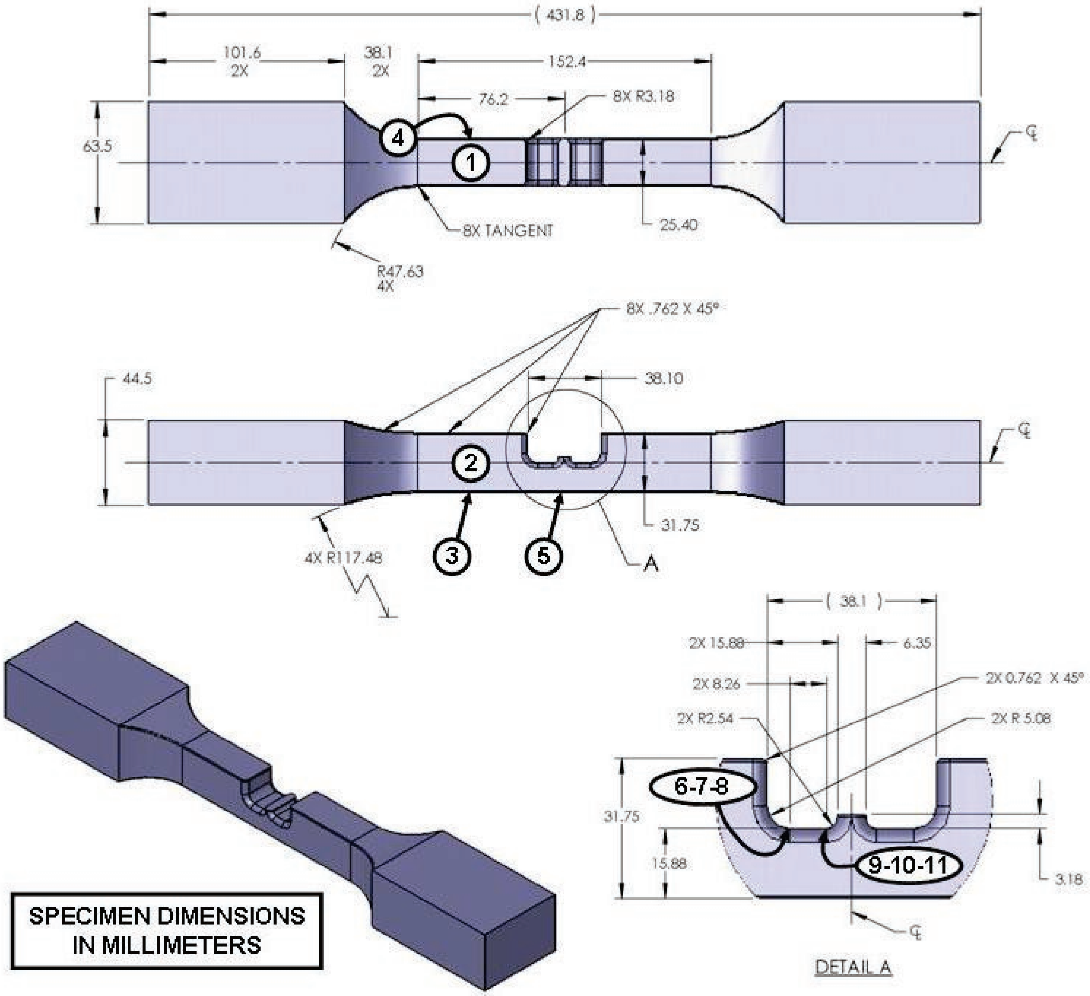

Figure 3. Schematic diagram of the fatigue specimen and the notch detail in the specimen. Encircled numeric identifications represent the locations of strain and strip gages on the specimen.

Results and Discussion

Conventionally shot peened (CP) specimens of Hy-Tuf steel qualitatively exhibit improvements in fatigue life over the unpeened specimens, and the laser peened (LP) specimens exhibit significant improvements in fatigue life over the CP specimens. Comparisons indicate that unpeened and CP specimens exhibit similar levels of fatigue life, whereas LP specimens exhibit a 250% improvement in the lower-bound estimate of crack initiation life, Figure 4.

The crack initiation lives of CP and LP specimens of Ferrium S53 steel also are shown in relation to the fatigue data for Hy-Tuf steel in Figure 4. These data indicate that laser peening provides significant improvements in crack initiation life over conventional shot peening in a coupon designed to mimic the high-stress region in an AHS. In comparison to Hy-Tuf steel, the increased strength of Ferrium S53 clearly provides significant increases in the crack initiation life of both the CP and LP specimens.

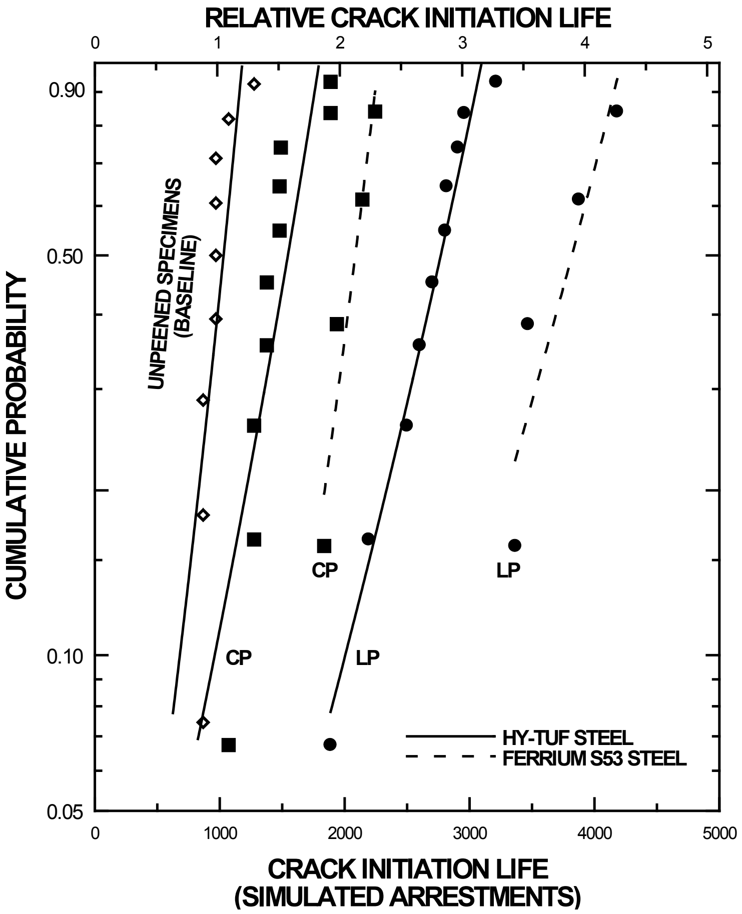

Figure 4. Cumulative distributions of crack initiation life are shown for unpeened, conventionally shot peened (CP), and laser peened (LP) specimens of Hy-Tuf and Ferrium S53 steel.

Fatigue tests on several specimens were continued to failure to obtain an indication of the relative effects of conventional and laser peening on crack propagation life as defined by the difference between total life and crack initiation life. The limited results of these tests, Table 1, indicate that conventional shot peening may provide some improvement in crack propagation life; however, the large depth of compressive residual stress introduced by laser peening significantly increases crack propagation life.

Table 1. Summary of Fatigue Life Data for Specimens Tested to Failure

MATERIAL	SPECIMEN	MATERIAL CONDITION	CRACK INITIATION LIFE (SIMULATED ARRESTMENTS)	TOTAL LIFE (SIMULATED ARRESTMENTS)	CRACK PROPAGATION LIFE (SIMULATED ARRESTMENTS)
HI-TUF STEEL	H2	UNPEENED	969	2591	1622
HI-TUF STEEL	H105	CONVENTIONALLY SHOT PEENED	1275	2693	1418
HI-TUF STEEL	H210	LASER PEENED + CONVENTIONALLY OVERPEENED	2601	6102	3501
FERRIUM S53 STEEL	F103	LASER PEENED + CONVENTIONALLY OVERPEENED	3927	6961	3034

Conclusions

The primary focus of this investigation is to evaluate the efficacy of laser peening on improving the crack initiation life in a severe arrestment hook shank application.

1. The shallow depth of compressive residual stress resulting from conventional shot peening provides marginal improvements in the mean crack initiation life of a fatigue specimen designed to simulate the critical region in an arrestment hook shank. However, conventional shot peening does not provide any improvement in lower-bound fatigue life.

2. The large depth of compressive residual stress resulting from laser peening provides significant improvements in both the lower-bound and mean crack initiation life of a fatigue specimen designed to simulate the critical region in an arrestment hook shank.

3. An increase in material yield strength from 1338 MPa to 1470 MPa substantially increases the crack initiation life of conventionally shot peened and laser peened specimens. High material strength in combination with laser peening is associated with the development of particularly high levels of fatigue life.

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References

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2. Aerospace Material Specification 5922 (Warrendale, PA: SAE International, 2008).
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