DURABILITY OF METAL AIRCRAFT STRUCTURES

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Preface

This monograph contains expanded written versions of the research work presented by a group of internationally-known experts on the subject of materials degradation and aging of aircraft structures at the "International Workshop on Structural Integrity of Aging Airplanes," 31 March - 2 April 1992, in Atlanta, Georgia. This workshop was sponsored by the Federal Aviation Administration, National Aeronautics & Space Administration, and the Air Force Office of Scientific Research.

This monograph is organized into these topical categories: (i) Prediction of Fatigue Damage, (ii) Repair Methodology and Reliability, (iii) Analytical and Test Methods in Fracture & Fatigue, (iv) Design Philosophy and Experience, (v) Mechanical & Corrosion Fatigue, (vi) Stiffened Shell Structures, (vii) New Materials and Processes to Improve Structural Integrity, (viii) Damage Tolerance & Residual Strength, and (ix) Flight Loads and Inspection.

Prediction of Fatigue Damage. In the first paper in this topical category, J. Schijve presents and analyzes results of fatigue tests on riveted lap joints, including fractographic observations. The second paper by Thomas Johansson and Hans Ansell deals with a simple method to estimate the contribution from different activities in the fatigue design procedure to a resulting failure risk, and with multiple-site-cracking in joints. The paper by Avraham Berkovits and Daining Fang describes work on identifying and relating monotonic and cyclic damage mechanisms in Incoloy 901 by use of acoustic emission. In the next paper, Beuth and Hutchinson present a two-dimensional plane stress elastic fracture mechanics analysis of a cracked lap joint fastened by rigid pins and apply their results to the problem of multi-site damage in riveted lap joints of aircraft fuselage skins. The paper by Rhonda Clement identifies the importance of establishing a suitable failure theory for widespread fatigue. The paper by Dawicke, Phillips, Swenson, and Gondhalekar deals with an experimental and analytical investigation of cracks growing from loaded countersunk rivet holes. In the final paper, Park and Atluri study the fatigue growth of multiple cracks of arbitrary lengths, emanating from a row of fastener holes in a bonded, riveted lap joint in a pressurized aircraft fuselage, by including the effects of residual stresses due to rivet misfit and plastic deformation near the fastener hole.

Repair Methodology & Reliability. The paper by Jones, Rees, and Kaye presents the results of an experimental investigation into the stress distribution and the load transfer mechanisms in a typical fuselage lap joint. Rooke, Young, and Courtney study the importance of some of the geometric and material parameters of adhesively bonded repair patches for the common aerospace structure of a stiffened sheet with a crack. Belytschko, Lewis, Moran, Harkness, and Platt outline the first order reliability and Monte Carlo Simulation methods for estimating the probability of fatigue failure and apply these methods in the setting where it is desired to establish crack-inspection cycles based on fatigue reliability. Paul Domas provides some of the information and experience gained in the Engine Structural Integrity Program of the U.S. Air Force in the arena of Probability of Detection.

Analytical and Test Methods in Fracture and Fatigue. Newman, Bigelow and Dawicke present a two-dimensional elastic-plastic finite element analysis with a critical crack-tip opening angle criterion to model stable crack growth in thinsheet 2024-T3 aluminum alloy under monotonic loading, along with some test results. Tan, Bigelow and Newman present solutions for stress intensity factors for corner cracks at a semi-circular edge notch in a plate subjected to remote tensile loading. Tong, Grief and Chen study the behavior of multi-site-damage by examining the interaction of cracks in stiffened, riveted joints. Potyondy and Ingraffea present a methodology for simulating curvilinear crack growth in the skin of a pressurized fuselage. Finally, Grigoriu and Ingraffea present a Monte Carlo simulation method to find optimal inspection times for aircraft components.

Design Philosophy and Experience. In the first paper, Lincoln presents the details of a probabilistic approach for determining the time of the onset of widespread fatigue damage that would degrade the fail safety of an aircraft structure. Marv Nuss provides an overview of the FAA's aging commuter airplane program. Richard Yarges presents the FAA's current plan for addressing the problem of aging transport airplanes. Schmidt and Brandecker discuss the aircraft industry's experience about parts potentially susceptible to widespread-fatigue damage, including the individual causes for multiple site damage or multiple element damage.

Mechanical & Corrosion Fatigue. Fine, Kung, Fadragas, and Achenbach discuss a database on the initiation of fatigue cracks defined as the lifetime to the smallest nondestructive-evaluation resolution. De Luccia discusses the materials and processes that have provided advances in corrosion control of aircraft. Koch discusses the effect of corrosion on the fatigue crack initiation and propagation in 2000 Series and 7000 Series aluminum alloys.

Stiffened Shell Structures. Miller, Kaelber, and Worden present a geometrically nonlinear finite element solution strategy for a fuselage structure containing cracks.

New Materials & Processes to Improve Structural Integrity. Clauer, Dulaney, Rice and Koucky present an overview of Laser Shock Processing and discuss how the process can be extended to treat fastener holes on aging aircraft. Fredell and Gunnick discuss how a new class of fiber metal laminates not only offer great advantages for new aircraft, but also can be applied to the damage tolerant repair of aging aluminum aircraft structures. Gentry, Ratwani, and Kudva present an assessment of smart structures concept with a particular emphasis on its application to aging aircraft. Piascik discusses environmental fatigue in aluminum-lithium alloys. Finally, Young summarizes the tests performed to evaluate the split sleeve cold expansion technique of fastenerholes in C-5 and L-1011 aircraft structural applications.

Damage Tolerance and Residual Strength. Swift discusses the need for a consideration of initial manufacturing damage to establish inspection thresholds for certain airframe principal structural elements by analytically demonstrating the need. Kosai, Kobayashi, and Ramulu propose a procedure based on dynamic fracture mechanics for assessing the effectiveness of tear straps in a rupturing airplane fuselage weakened by a row of multiple site damage. Cummins, Jefferson, and Lambert discuss an analysis technique for widespread fatigue damage. Finally, Terada discusses the elements to be taken into consideration for a full-scale and damage-tolerant testing to assure the structural integrity of aging aircraft.

Flight Loads and Inspection. Ottens and de Jonge present an overview of the FAA and the Netherlands Civil Aviation Department RLD programs related to aging aircraft.

It is thus seen that this monograph contains an excellent summary of the worldwide activities aimed at an evaluation of the structural integrity of aging metal aircraft structures.

The editors thank all the contributing authors for their diligence in preparing their articles in a timely fashion The editors also thank Ms. Barbara Durham for her assistance in preparing this monograph for publication.

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Atlanta, Georgia; November, 1992

Laser Shock Processing for Treating Fastener Holes in Aging Aircraft

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Abstract

This paper presents an overview of Laser Shock Processing and then discusses how the process can be extended to treat fastener holes on aging aircraft. The process is used to treat localized fatigue-critical areas by developing deep residual compressive stresses to inhibit the initiation and propagation of fatigue cracks. This feature can be applied to fastener holes in aircraft structures to determine whether the fatigue life associated with the failure in these areas can be increased.

Introduction

Laser Shock Processing (LSP) has become a commercially viable process within the last few years with the design, construction and operation of a prototype laser that is very compatible with a manufacturing environment in size and capability. While still in the development stage, its ability to develop deep, high compressive stresses in the areas treated has been demonstrated on a number of metals and alloys. There have also been demonstrations of large improvements in the fatigue life and fatigue strength in various metals and alloys. In this paper, the laser shocking process and representative examples of property improvements in aluminum and steel will be discussed. In addition, the application of the process to treat fastener holes in aging aircraft will be discussed.

Description of the Process

This laser process works through a mechanical, not thermal, mechanism. The action of a stress wave passing into the surface being treated causes deformation of the surface layer and this deformation results in a surface residual compressive stress. The laser being used is a pulsed laser having a wavelength of 1.06 microns. The duration of the pulse is nominally 20 nanosec-onds. The laser spot diameters are typically 5 to 10 mm (0.2 to 0.4 inches), but larger areas can be treated by applying a series of overlapping spots.

A schematic of the process is shown in Figure 1. Before shock processing a specimen or part, two overlay materials are applied over the area to be treated on the surface. A layer of black paint is first applied to protect the surface. Without the paint a very thin melt and recast layer forms on the surface, which may be undesirable. To enhance the magnitude of the treatment, an overlay transparent to the laser beam is placed over the black paint. This can be any material transparent to the laser beam, but for most purposes a practical material is flowing water.

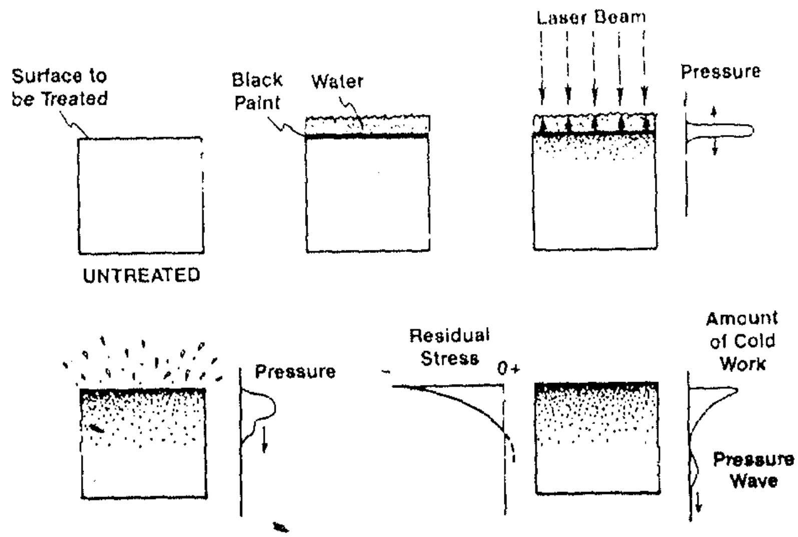
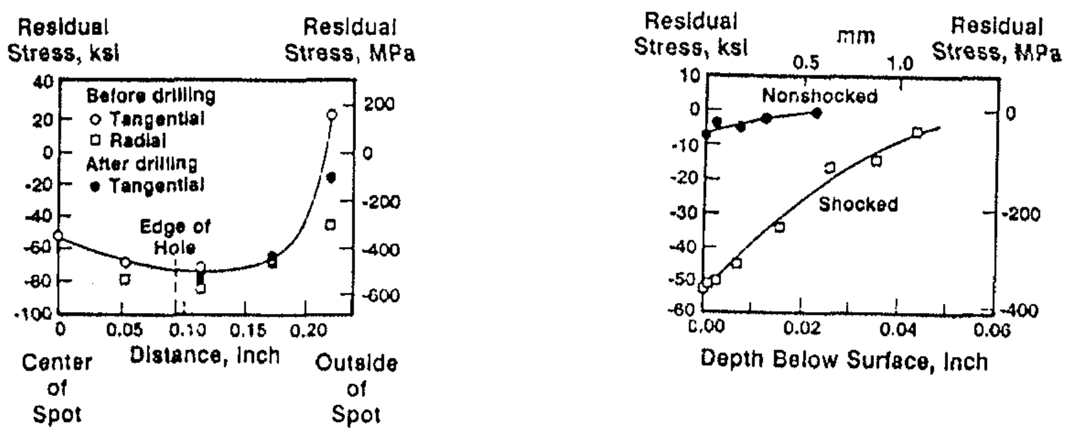


Figure 1. Schematic of the Laser Shocking Process, Showing the Overlays and the Action of the Pressure and Associated Stress Wave to Produce a Surface Residual Compressive Stress

When the laser beam is turned onto the area to be treated, it passes through the transparent overlay and is absorbed initially by the paint. The energy of the beam immediately vaporizes a very thin layer of the paint. This vapor then absorbs the remainder of the incoming laser energy, causing it to heat and expand very rapidly. By confining this rapidly expanding gas against the surface by the water overlay, pressures in the range of 3500 to 6900 MPa (500,000 to 1,000,000 psi) are created [Fairand and Clauer (1979)]. As a result of this pressure, high amplitude stress waves are transmitted both into the surface of the part and into the water overlay. The stress wave propagating into the water blows the water off the surface, but the one propagating into the metal surface plastically deforms the material in and under the surface. The depth of this deformation extends to the depth where the peak stress of the stress wave is no longer greater than the yield strength of the material The result of the plastic deformation is a surface residual compressive stress over the area being treated.

Residual Stress Distributions

A typical residual stress distribution across a laser treated spot is shown in Figure 2a in 7075-T6 aluminum. The residual stresses were measured using X-ray diffraction. The measurements were made at intervals along the radius of the spot from the center to just beyond the outside edge. The open points show there were no differences in the stresses measured in the radial and tangential direction within the spot, as expected. Just outside the spot, the stresses in the tangential direction are tensile, but the radial stresses remain compressive. The tangential tensile stresses are balancing the tangential compressive stresses inside the treated zone. After the open circles were measured, a hole was drilled and the tangential stresses were again measured (the filled circles in Figure 2a). There was no change except for some reduction in stress just outside of the spot.



a. Distribution Across the Treated Spot in 7075-T6 Aluminum

b. In-Depth Distribution in 2024-T3 Aluminum

Figure 2. Residual Stress Distributions in Laser Shocked Aluminum Alloys

The depth of the residual stresses below the treated surface is shown in Figure 2b in 2024-T3 aluminum [Clauer, Walters, and Ford (1983)]. Both shocked and unshocked conditions are compared. The stresses were measured in depth by sequentially electropolishing away layers and making measurements. The stresses are highest at the surface and decreased uniformly with increasing depth. The surface stress is about the level of the yield strength of the alloy and extends to over 1 mm (0.040 inch) below the surface. This is deeper than shot peening, which usually extends 0.3-0.5 mm (0.010 to 0.20 inch) below the surface. In most other materials the maximum residual stress is usually some fraction of the yield strength, but more than half. In all the metals investigated so far, the residual stresses extended deeper than is typical of shot peening.

Fatigue Properties in Aluminum

The residual compressive stresses would be expected to improve fatigue properties by inhibiting the initiation and propagation of cracks. This was investigated in several ways in aluminum alloys; for fretting fatigue around a fastener hole, for fatigue of a notched hole and for a precracked hole. Other configurations were investigated in other metals and alloys, but except for a side-notched configuration in steel, these will not be discussed in this paper.

The fretting fatigue properties were investigated in 7075-T6 "dogbone-type" specimens as shown in Figure 3. The regions around the fastener hole in the specimen and the pad were laser shocked with a laser spot diameter of 13 mm (0.52 inch). Both sides were shocked simultaneously. The metal surface immediately outside of the shocked areas were then carefully ground away so that all the load from the fastener would be concentrated on just the laser shocked region. The fastener was a steel aerospace quality fastener with 30 percent load transfer. The fretting fatigue results are shown in Figure 4. Laser shocking increased the fatigue lives at least two orders of magnitude at a stress amplitude of 96 MPa (14,000 psi). At the highest stress level the fatigue life was still approximately doubled. Inspection of the fracture surfaces showed no discernable differences between the shocked and unshocked specimens [Clauer and Fairand (1979)].

The effect on fatigue life of laser shocking around a hole was investigated in 2024-T3 aluminum for the specimen and hole configuration in Figure 5. The hole, located in the center of the gauge length, has small starter notches machined into its sides as shown in the Figure. The region around the hole was treated in two different patterns. In one case a solid spot was used to treat the entire region around the hole as shown by the cross-hatched area. In the other case, only the annular-shaped area shaded with dots in Figure 5 was shocked. In the first case a crack both initiated and propagated through laser shocked material, but in the second case it initiated and initially propagated in unshocked material, then encountered the laser shocked region. The fatigue life increases for these two cases are shown in Figure 6 as crack length versus cycles.

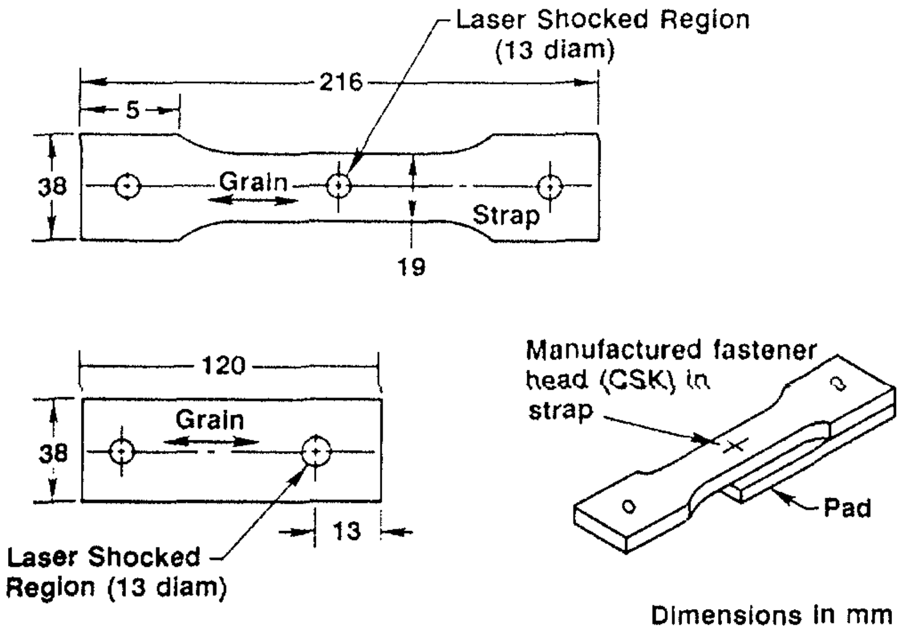


Figure 3. Specimen Configuration for the Fastened, Fretting Fatigue Specimen. All Dimensions are in Millimeters

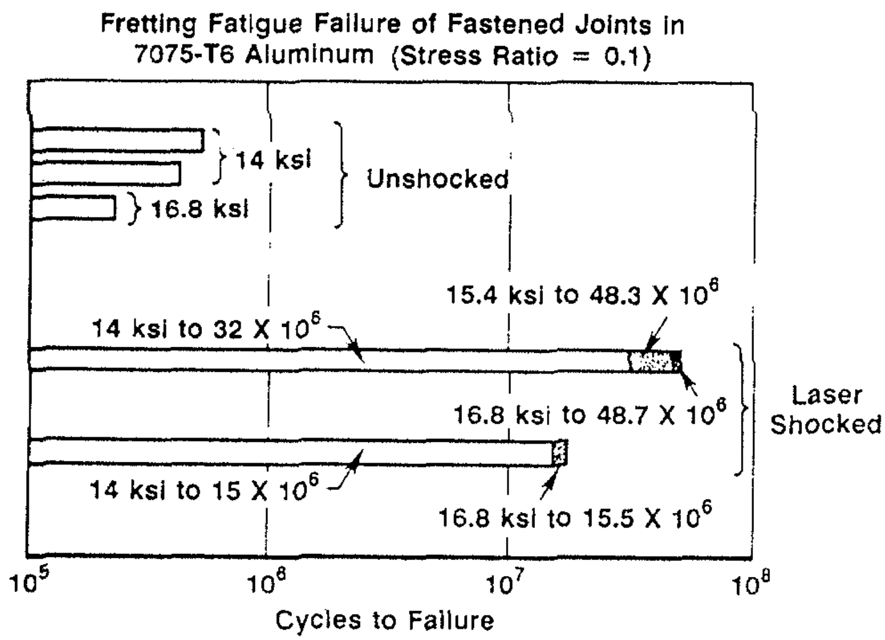


Figure 4. Fretting Fatigue Lives of Laser Shocked and Unshocked Specimens of 7075-T6 Aluminum Tested at a Stress Ratio of 0.1

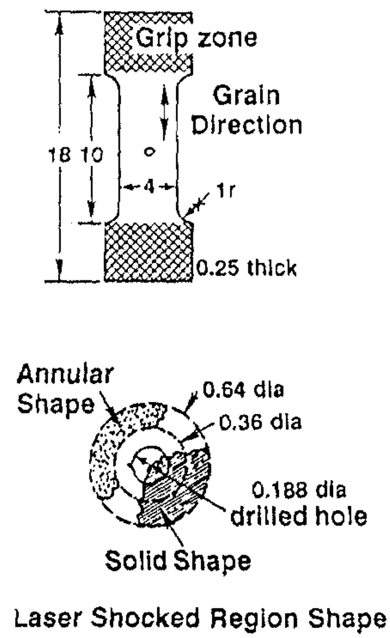
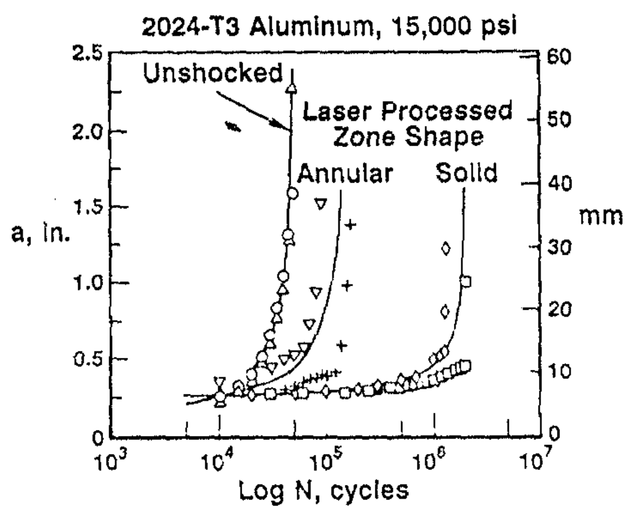


Figure 5. Specimen Configuration and Laser Shocking Arrangement for Tensile Fatigue Specimens Containing a Hole. The Dimensions are in Inches



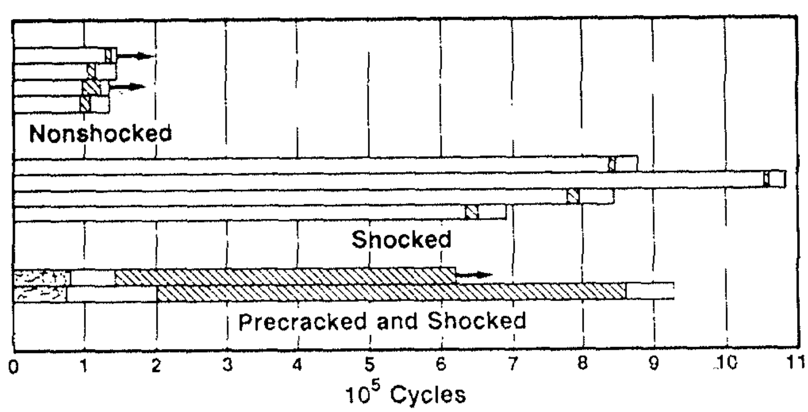
- Laser beam can have different shapes
- Solid shape is most effective

Figure 6. Fatigue Lives of Shocked and Unshocked Specimens of 2024-T3 Aluminum Having the Configuration Shown in Figure 5. Tested at a Stress Ratio of 0.1

Compared to the unshocked condition, the specimens shocked with the annular-shaped spot had an increase of about three times in cycles to failure, whereas those shocked with the solid spot had an increase of forty times. While it wasn't possible to determine from these results whether crack initiation is affected by laser shocking (crack initiation occurred at mid-thickness in the notch root), it is clear that it slows crack propagation.

To examine this further, precracked specimens were also laser shocked and tested. The specimens were the same size as those shown in Figure 5, but had radiused notches instead of sharp notches at the sides of the hole. After precracking to form a crack 0.5 mm (0.020 inches) long, the material ahead of the crack was laser shocked. After laser shocking, the fatigue lives of the precracked specimens were still increased about four times compared to unshocked, not-precracked specimens, and retained about the same life as that of laser shocked, not-precracked specimens (Figure 7). The initial speckled region in the bars for the precracked specimens indicates the number of cycles to grow a crack 0.5 mm long. The cross hatched region indicates the number of cycles to grow the cracks from 6 to 11 mm (0.25 to 0.45 inches) long. Thus, preexisting cracks can be significantly slowed, and the life of cracked specimens increased by laser shocking the region ahead of the crack.

Figure 7. Fatigue Lives of Specimens With and Without Cracks Before Laser Shocking. The Speckly Shaded Bars are the Cycles to Grow a 0.5 mm Long Crack. The Cross-Hatched Bars



Represent the Cycles to Grow the Crack from 6 to 11 mm Long.

Fatigue Properties in Steel

Thc aluminum specimens discussed above were all 6 mm (0.25 inches) thick, whereas for application to aging aircraft the skin material is usually 1 mm (0.040 inches) thick. There are fatigue results for steel sheet 1.5 mm (0.060 inches) thick that show that large increases in fatigue strength can also be achieved in thin sections.

The steel was AISI 4340 steel heat treated to Re 54 hardness. The specimen configuration is shown in Figure 8, where the region between the notches was laser shocked. The shocking was done from both sides simultaneously. The specimens were tested in tensile fatigue at R= 0.1. The unshocked properties in Figure 9 are defined by the two points at low fatigue life and the nominal handbook value of fatigue strength at long life. The laser shocked specimens were first tested at 690 MPa (100,000 psi) stress amplitude. These were run out to nearly 10,000,000 cycles, then the stress amplitude was raised to 965 MPa (140,000 psi) and one specimen was again run out to nearly 10,000,000 cycles. After raising the stress to 1100 MPa (160,000 psi), the specimens failed at the cycles shown, still an increase in life over the unshocked condition. The fatigue strength was increased from nominally 586 MPa (85,000 psi) to nominally 1033 MPa (150,000 psi), about a 70 percent increase [Tucker and Clauer (1983)]. Whether this same level of improvement could also be produced in aluminum sheet is not known, but something similar to this could be reasonably expected.

Applications

The process has been demonstrated to significantly increase fatigue life. The residual stresses are deeper than those produced by shot peening and would be expected to have a commensurately greater effect on fatigue life and fatigue strength. Since the process is not yet practical for treating large areas, it will be best used to treat localized fatigue critical areas of parts and structures, including weldments and those subject to fretting fatigue failure. It also cold works material through thin metal sections and can be used to locally strengthen the material. It could also be used in conjunction with shot peening or other cold working methods to extend fatigue life. Combinations of these methods could provide greater overall success than the use of any one of them alone.

Localized fatigue critical areas would generally be associated with stress raisers such as holes, notches, keyways, fillets, and gear teeth. Typical applications would include turbine blades and disks, rotating shafts, gears, reciprocating parts, connecting rods and prosthetic devices. Also included would be cyclically loaded structures such as aircraft structures and skins. In aging

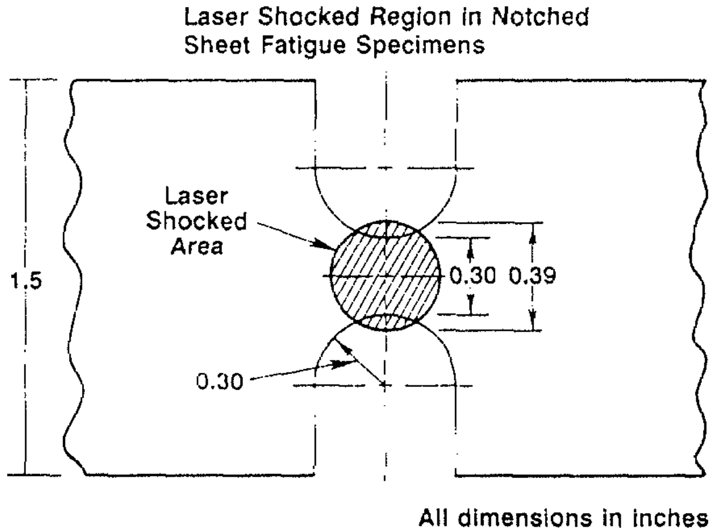


Figure 8. Specimen and Laser Shocking Configuration for the Thin, AISI 4340 Steel Sheet. The Dimensions are in Inches

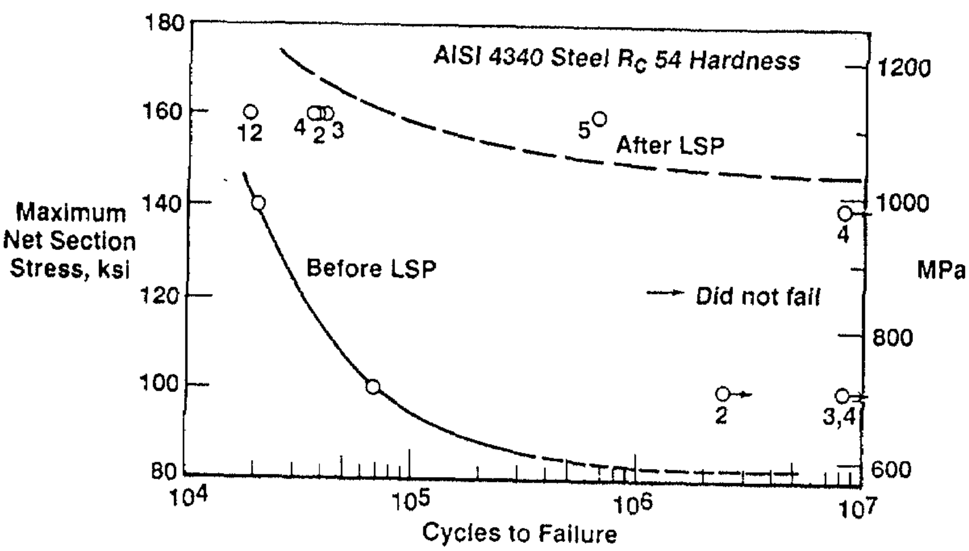


Figure 9. Fatigue of Shocked and Unshocked AISI 4340 Steel Sheet Heat Treated to R_c 54. Tested at a Stress Ratio of 0.1

aircraft, there is a need to treat fastener holes and perhaps other areas in aircraft already in use, but needing repair.

The primary areas of concern for crack initiation in fastener holes are at the sharp edge of the sheet at the bottom of the countersink and along the slope of the countersink where fretting may contribute to crack initiation. There may also be some crack initiation associated with the top edge of the fastener where it bears on the sheet at the top of the countersink. Considering that there may well be cracks present in these regions below the inspectable limit, one of the beneficial features of laser shock processing is that it can significantly retard the growth of these cracks that are missed.

Laser shock processing offers the possibility of treating fastener holes in several ways (Figure 10). The preferred situation would be to laser shock the holes with the fasteners left in place, and to treat from one side only. It is not known how this might work. It may be that two sided processing will be more desirable in some cases, or that the fastener be removed before laser shocking. These process configurations are also shown in Figure 10. The determination of which of these approaches would be best would depend on the magnitude of the improvements achieved and the tradeoffs relative to how each approach fits with the various maintenance cycles and procedures.

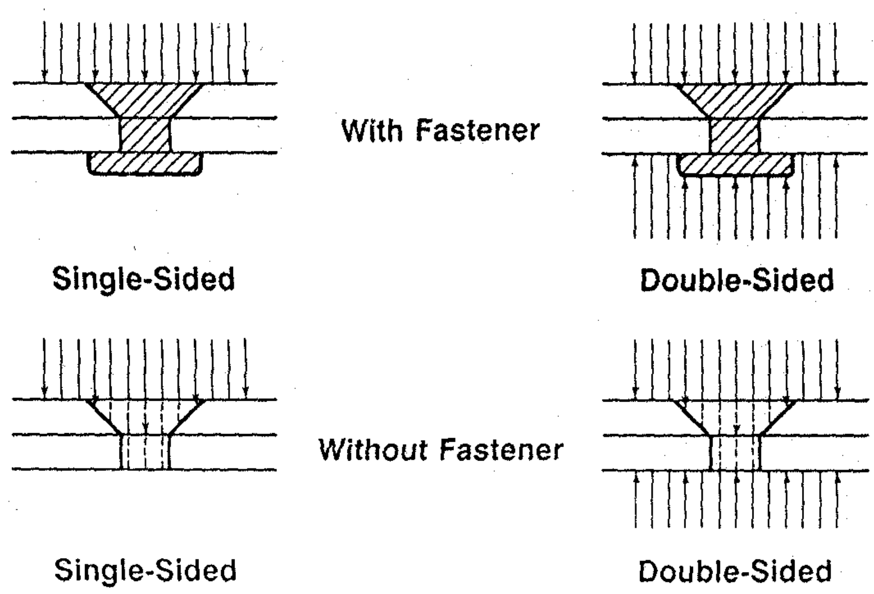


Figure 10: Possible Configurations for Laser Shock Processing of Fastener Holes

Quality Control and Assurance

There are a number of methods available to monitor the processing of holes. First, the energy and pulse length of each pulse can be measured and matched against a standard for each shot. Second, the paint film or other overlay will show the effects of the shot. This effect could probably be quantified against some standard also. Third, there is a mechanical impulse imparted to the surface being treated. A contact probe placed in the vicinity of the treated hole could at a minimum detect the presence of the impulse and perhaps could also be calibrated in some way to monitor the magnitude of the impulse. In a softer metal such as aluminum, there will also probably be a very shallow indentation of the treated area. The depth of this depression decreases as the laser intensity decreases, but is typically 10 to 25 microns (0.0002 to 0.001 inch) deep. In harder materials such as steels this effect is so small that on a typical machined surface it is very difficult to discern the treated area.

Overlays

There may be some concern over the use of black paint and water overlays, with the desire to have a dry overlay instead. Black paint and water have been the primary overlay materials used because they work and there has been no critical application yet identified that will not tolerate either black paint or water. However, it is likely that dry, expendable overlays can be developed for those applications that require them.

Laser Equipment

A prototype laser has been developed which is very compatible with a manufacturing setting. It has a pulse rate of one every four seconds with an ultimate design rate of one Hertz. The laser occupies a space nominally 1.5 by 2 m (4 by 6 feet) and could either be set in place or be semi-mobile. It is modular in design, allowing the power of the laser to vary by a factor of at least four with little increase in physical size. The prototype has demonstrated good reliability and various maintenance issues have been identified and resolved at this prototype stage, avoiding these problems later.

Summary

It has been demonstrated on many alloys that laser shock processing produces deep, high level, residual compressive stresses that significantly increase fatigue life and fatigue strength. A prototype laser has operated reliably for almost two years and has a flexible, modular design that lends itself readily to the design and construction of a commercial laser.

The process should be extended to demonstrating its application to fastener holes in aging aircraft, to determine the magnitude of the benefits it may offer in treating feather-edged holes and thin sheet.

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