RECENT DEVELOPMENTS IN THE JOINT STRIKE FIGHTER DURABILITY TESTING

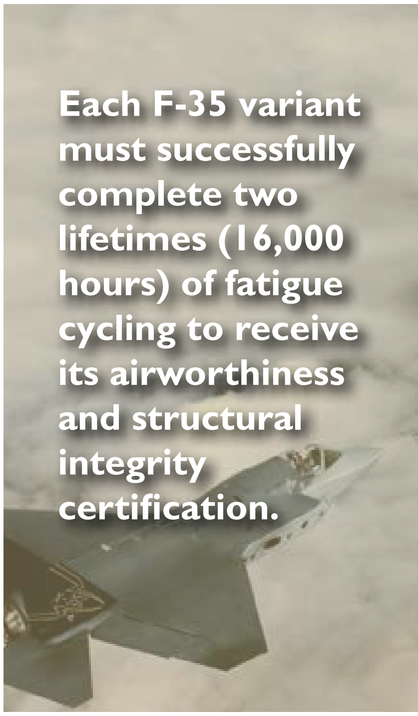
Lisa Veitch and Evan Laprade

The Problem

The Joint Strike Fighter (JSF) program—the largest defense acquisition program in history—aims to maintain U.S. air superiority by providing the next generation of Air Force, Navy, and Marine Corps fighter aircraft. It is also, arguably, the most complex defense acquisition program ever undertaken. IDA's role is to assess progress in developmental testing for USD(AT&L), exploring potential issues and testing options for consideration by the program office and by other stakeholders in the acquisition process.

F-35 DURABILITY TESTING PROGRAM OVERVIEW

The Joint Strike Fighter (JSF)/F-35 Lightning program, the Defense Department's most expensive acquisition program, is currently more than halfway through developmental test and evaluation (DT&E). Three variants of the aircraft, shown in Figure 1, are to be delivered to the Air Force, Marines, and Navy within the next five years. Each has unique capabilities. The Air Force variant is the conventional take-off and landing (CTOL) aircraft; the Marine variant is a short take-off/vertical landing (STOVL) aircraft, which can operate in austere locations; and the Navy's carrier variant (CV) is equipped for landing on carrier decks. Developmental testing (DT) of each variant requires not only flying the aircraft to analyze its flight characteristics and mission systems, but also involves full-scale ground testing to determine each design's structural integrity.



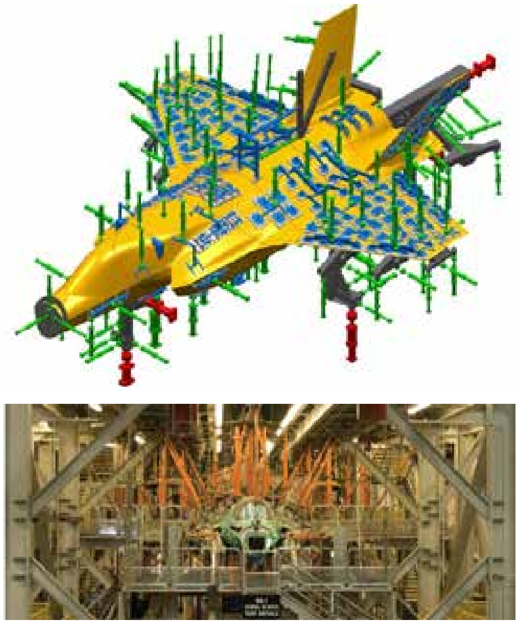
Each F-35 variant must successfully complete two lifetimes (16,000 hours) of fatigue cycling to receive its airworthiness and structural integrity certification.

Source: Images courtesy of Lockheed Martin.

Figure 1. JSF Variants: (left to right) F-35A (CTOL), F-35B (STOVL), F-35C (CV)

Each F-35 variant must successfully complete two lifetimes (16,000 hours) of fatigue cycling to receive its airworthiness and structural integrity certification. To demonstrate this capability, a complete airframe is subjected to a spectrum of maneuver, buffet, and catapult/arrestment (carrier variant only) loads, using a specially designed rig of pneumatic jacks

(Figure 2). Each test article is heavily sensored to monitor strain and stress loadings of critical areas. Through this full-scale durability testing, the F-35 program hopes to identify points in the structure that do not meet durability requirements, incorporate fixes for these issues (when possible), and, most importantly, demonstrate that the airframe design will maintain its structural integrity as required.

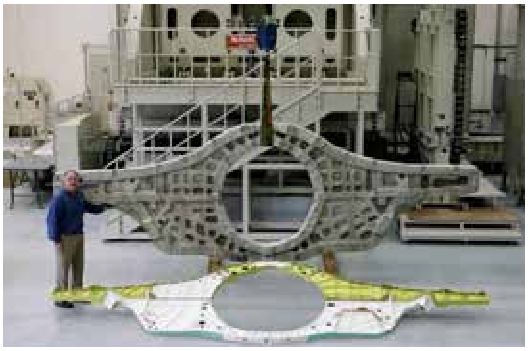


Source: Images courtesy of Lockheed Martin.

Figure 2. (Above) Schematic Showing Location of Approximately 150 Pneumatic Loading Points; (Below) STOVL Test Article Sitting in Its Test Fixture

FIXES TO ACHIEVE "FULL-LIFE" – REDESIGNS, STRAPS, AND LASERS

Since 2010, IDA has been closely monitoring the progress of the F-35 durability testing program in support of Deputy Assistant Secretary of Defense (Developmental Test and Evaluation) (DASD DT&E) assessments. During this time, an unexpected number of structural and materials issues have arisen. In particular, testing the STOVL full-scale article, referred to as BH-1, has been, and continues to be, particularly eventful. BH-1 began testing in July 2010 and shortly thereafter inspections discovered a succession of significant cracks at approximately 1,500, 7,000, and 9,000 hours of testing. These cracks occurred in major load-bearing bulkheads (like that shown in Figure 3), which hold the wings onto the aircraft and are essential to the structural integrity of the airframe.



Source: Images courtesy of Lockheed Martin.

Figure 3. STOVL Bulkhead 496, Forged from Aluminum 7085

As a result of these design shortfalls, BH-1 has required extensive repairs and experienced significant downtime, setting testing progress behind by more than a year and a half. Furthermore, due to the production and testing concurrency of the F-35 program, these failures now must be addressed as retrofit fixes for earlier low rate initial production (LRIP) aircraft, and, when possible, as bulkhead redesigns for future production aircraft, creating myriad configurations that must be certified.

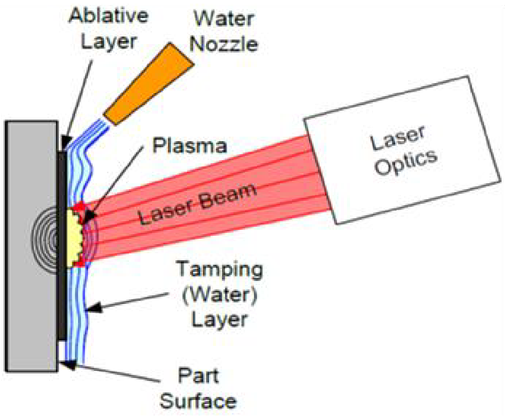
For instance, for pre-LRIP 5 aircraft, the fatigue life shortfalls identified at 1,500 hours of testing require the addition of heavy steel straps (mechanically attached reinforcement braces). For post- LRIP 5 aircraft, a bulkhead redesign, with thicker features, is being used for production. Similar modifications—straps for early production and redesigns for future production aircraft—will help address the shortfalls identified at 7,000 hours. The fatigue life shortfalls identified at 9,000 hours, however, pose a greater challenge because the necessary bulkhead redesign (thickening of features) cannot be accommodated without interfering with neighboring components. As a result, Lockheed Martin is pursuing a special method to strengthen these bulkhead areas—a unique surface treatment process referred to as Laser Shock Peening (LSP).

LASER SHOCK PEENING (LSP)

LSP is a *mechanical* process that improves a material's fatigue life by introducing a compressive residual stress at the surface. A material's surface, where there is often a combination of high strain (or stress), stress concentrations (sharp design features, machining marks), and corrosive attack, is particularly susceptible to fatigue crack initiation. A compressive surface stress layer counteracts the tensile stress environment necessary for crack nucleation and growth, thereby improving a material's crack resistance and fatigue life.

LSP uses high-energy laser pulses to create a shock wave that mechanically deforms the surface of a material (it is not used to create thermal effects). The process, shown in Figure 4, involves first coating the part surface with a sacrificial ablative layer (typically paint or tape). Water is then flowed over the part surface and a high-energy laser (1-10 GW/cm2)[1] is directed at the target region. A laser pulse vaporizes the ablative layer, creating a plasma cloud that is confined by the water layer. The rapidly expanding plasma generates a pressure shock wave (1-10 GPa)[2] that plastically compresses the metal, producing a residual stress field with a highly controllable depth and magnitude.

While LSP generates compressive stresses similar in magnitude to that of traditional shot-peening methods, the depth of this residual stress field extends far deeper below the surface (up to 2 mm for LSP versus only 0.5 mm for shot peening).[3]



Source: Graphic reproduced from LSP Conference Presentation, April 2010, F-22 Air Vehicle Technology.

Figure 4. Laser Shock Peening Schematic

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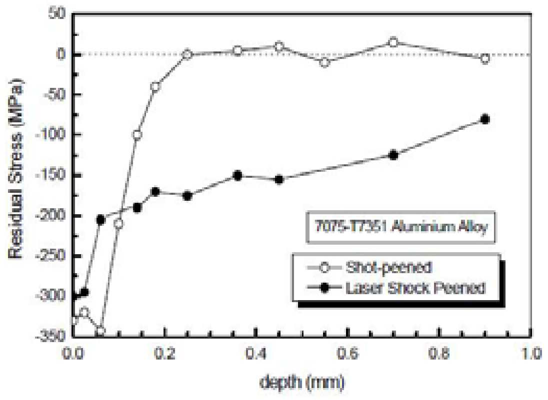
[1] Y. B. Guo, "Laser Shock Peening: Modeling, Simulations, and Applications," in *Numerical Simulations – Applications, Examples and Theory*, ed. Lutz Angermann (InTech, January 2011), 331–54.

[2] Y. Zhao, "Effects of Laser Shock Peening on Residual Stress, Texture and Deformation of Microstructure of Ti-6Al-4V Alloy" (Ph.D. diss., University of Cincinnati, 2012).

Figure 5 provides a comparison between the residual stress produced in an aluminum alloy using traditional shot peening and laser shock peening, with the latter exhibiting a significantly deeper compressive stress field.



Source: Q. Liu, "An Effective Life Extension Technology for 7xxx Series Aluminum Alloys by Laser Shock Peening," DSTO-TR-2177 (Melbourne, Australia: Defence Science and Technology Organisation, 2008), http://dspace.dsto.defence.gov.au/dspace /handle/1947/9655.

Figure 5. Comparison of Residual Stress Fields Induced by LSP and Shot Peening in Aluminum Alloy 7075-T7351

As a result, LSP provides resistance to crack growth and initiation deeper below the surface, further improving fatigue life. Additional advantages of LSP (versus shot peening) include process repeatability, less surface damage (cratering), and greater flexibility to reach hard-to-access areas.

Laser shock peening was initially demonstrated in the 1960s, but technology maturation delayed industry adoption until the mid-1990s. During the decade that followed, LSP found particular success extending the lifetime of engine fan blades, including those on the B-1B Lancer, F-16 Falcon, and Boeing's 777/787.[4] More recently, LSP has been applied to airframe structures as shown in Figure 6: F-22 Raptor titanium (Ti) wing lug,[5] T-45 steel tail hook shank,[6] and Apache/Chinook steel rotor gears.[7] LSP processing of aluminum aircraft structures has been limited to 747-8 wing panel skins[8] and T-38 aircraft main landing gear aluminum side-brace trunions (7049-T73).[9]

The F-35B bulkheads that require LSP processing are made from a relatively new 7000 series aluminum, aluminum (Al) 7085. Although a number of laboratory studies on 7000 series

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[3] Ibid.

[4] Q. Liu, "An Effective Life Extension Technology for 7xxx Series Aluminum Alloys by Laser Shock Peening," DSTO-TR-2177 (Melbourne, Australia: Defence Science and Technology Organisation, 2008), http://dspace.dsto.defence.gov.au/dspace /handle/1947/9655; L. Hackel, "Corrective laser peen forming of F-18 fuselage 701 skins," CTMA Symposium, 2012.

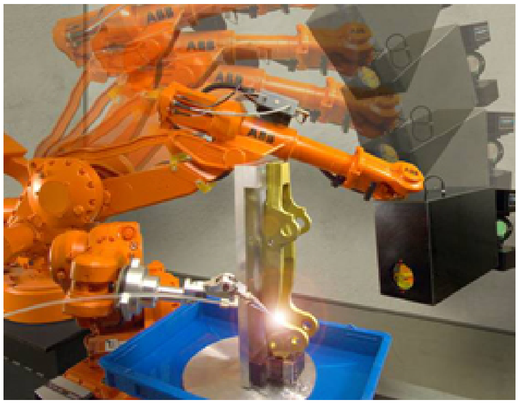
[5] D. Jensen, "Adaptation of LSP Capability for Use on F-22 Raptor Primary Structure at an Aircraft Modification Depot," 2nd International Laser Peening Conference, San Francisco, CA, April 2010; L. Polin et al., "Full Scale Component Tests to Validate the Effects of Laser Shock Peening," F-22 Program Brief, Public Release 11/18/2011, 2011.

[6] J. Rankin et al., "Effect of Laser Peening on Fatigue Life in an Arrestment Hook Shank Application for Naval Aircraft," 2nd International Laser Peening Conference, San Francisco, CA, April 19, 2010.

[7] "Laser Peening for Army Vehicle Life Extension," SBIR Award ID 62903, 2008, http://sbir.gov/ sbirsearch/detail/218723.

[8] C. Collisson, "Re-inventing the Legend: The Development of the 747-8," ICAS 2008, 2008.

[9] Liu, "An Effective Life Extension Technology for 7xxx Series Aluminum Alloys by Laser Shock Peening."



Source: Image courtesy of Metal Improvement Company.

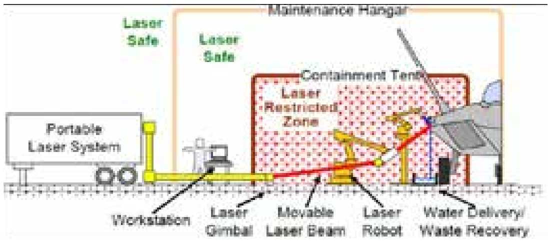
Figure 6. Time Lasped Images of an LSP Operation – LSP Robot (orange) Controls Laser (black box) Positioning and Water Injection (silver nozzle) as a Metal Part Is Processed

aluminum have demonstrated that LSP provides a significant fatigue life improvement (~3x or more) relative to the as-machined condition,[10] only a single published research effort[11] has looked specifically at LSP processing of Al 7085.

LSP DEVELOPMENT PROGRAM

An LSP development program is currently under way by Lockheed Martin to optimize process parameters for Al 7085 and to verify that LSP will provide the necessary fatigue life enhancement. The F-22 wing-lug development effort provides a useful frame of reference for assessing the road ahead for LSP qualification for F-35 bulkheads. The F-22 wing-lug LSP qualification process was completed over a four-year period, starting with coupon level testing to optimize LSP parameters—laser intensity, pulse size, duration, and number of layers (LSP parameters are highly dependent on material and geometry).

The LSP setup used for the F-22 consists of a tractor-trailer-mounted laser system and a robot that redirects the laser to the target area (see Figure 7). F-22 wing lugs are relatively easy to access after removing the aircraft's wings, providing adequate space for robot positioning and water jet placement. Access to the F-35 bulkheads will be more restricted and will likely require even greater engineering efforts in terms of aircraft disassembly, laser redirection, and water flow positioning. In addition, material and part design differentiates the F-35 bulkhead LSP development effort from that of the F-22 wing lug. The bulkhead features that have been targeted for LSP treatment are primarily webs and flanges. These features are considerably thinner and geometrically more complex than those processed on the wing lug, making residual stress control more challenging.



Source: Jensen, "Adaptation of LSP Capability for Use on F-22 Raptor Primary Structure at an Aircraft Modification Depot."

Figure 7. LSP Setup Used for the F-22

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[10] Ibid.; Montross et al., "Laser shock processing and its effects on microstructure and properties of metal alloys: a review," International Journal of Fatigue 24, No.10 (2002), 1021–1036.

[11] H. Luong and M. Hill, "The effects of laser peening on high-cycle fatigue in 7085-T7651 aluminum alloy," Materials Science and Engineering: A 477, No.1-2 (2008), 208–216.

PATH TO STOVL AIRCRAFT CERTIFICATION

The airworthiness and longevity of the F-35B is critically dependent on the successful qualification of the LSP process. Currently the LSP development effort is on schedule for completion in November 2017. Assuming this timeline holds, the first production line cut-in of LSP would start with LRIP 11 (all STOVL aircraft LRIP 11 and beyond would receive LSP during production). Pre-LRIP 11 STOVL aircraft (111 in total), however, will undergo LSP processing as part of a depot modification. Given LSP's significance to the entire F-35B fleet, IDA continues to monitor the progress of the LSP development program and provide DASD DT&E with technical insights on this important piece of the durability testing program.

Dr. Veitch is a Research Staff Member in IDA's System Evaluation Division. She holds a doctorate in materials engineering from Purdue University.

Dr. Laprade is a Research Staff Member in IDA's System Evaluation Division. He holds a doctorate in materials science and engineering from Northwestern University.

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