Presented at the ASME/JSME 2004 Pressure Vessels and Piping Division Conference, San Diego, CA, July 25-29, 2004

APPLICATIONS OF LASER PEENING T0 TITANIUM ALLOYS

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ABSTRACT

Laser peening has been a commercial surface enhancement process for over six years, and has been gradually expanding the number of applications being laser peened in production ever since. LSP Technologies has been a major developer of the process and new applications for laser peening. It has developed production laser peening systems and innovative laser peening technology to increase throughput and reduce cost. Some of these production and technology developments will be discussed in this paper. Also, an evaluation of applying laser peening to increase the fretting fatigue resistance of titanium alloys, based on Ti-6Al-4V has been made. Included in this evaluation is the use of small spot laser peening to enable the processing of the inside of small, generally inaccessible areas such as the insides of holes and slots. Laser peening with either large or small spots dramatically increased the fretting fatigue life under both R=0.5 and R=0 fatigue conditions with three different contact pad pressures. Fretting fatigue life was increased by at least 25 times. Actual increases in fatigue life and fatigue strength could not be determined because most specimens ran to the runout life of 10^6 cycles without failure. The laser peening does not appear to affect the fretting behavior, but instead inhibits the initiation of fatigue cracks at the fretting cracks developed from the fretting process. The compressive residual stress from laser peening also would slow the growth rate of any fatigue crack that does eventually initiate at a fretting crack.

INTRODUCTION

LSP Technologies has designed and built two production laser peening systems with the support of the Air Force Materials and Manufacturing Directorate. In 2003 it began production laser peening of an integrally bladed rotor for the F119 engine being built by Pratt & Whitney. To increase throughput and reduce the cost of the process, several technology improvements have also been developed and are being implemented into production. Among these is the RapidCoater™ system, which allows continuous processing of a part.

Under a NAVAIR Phase II SBIR, LSP Technologies has investigated the effect of laser peening on fretting and fretting fatigue in dovetail slots. An outcome of this program is a laser peening system that enables the interior of dovetail slots to be accessed by laser peening. Because of the dovetail geometry, small spots (< 1mm in diameter) and underwater laser peening were used to treat the interior of the slots.

TECHNOLOGY DEVELOPMENTS FOR AFFORDABLE LASER PEENING

In traditional laser peening, an opaque overlay coating, usually paint or tape, is applied to a part before laser peening. The coating provides a uniform surface for processing and protects the part from being marked by the laser beam. Normally, the opaque overlay must be reapplied manually multiple times during processing of the part. The reapplication of the overlay coating may be labor intensive for complex parts and detracts from the cost effectiveness of the process.

With support from the U.S. Air Force ManTech Laser Peening Initiative, LSP Technologies, Inc. developed the RapidCoater™ system, which eliminates the manual reapplication of the overlay coating. A picture of the RapidCoater™ system is shown in Figure 1. The RapidCoater™ system is essentially a computerized system for sequencing the following steps: (1) spraying of a specially developed opaque overlay coating, (2) application of the water overlay, (3) triggering the laser pulse, and (4) cleaning the surface in preparation for the next spot. The spray system nozzles are specially designed for operation in confined areas. With the RapidCoater™ system, laser peening may be performed continuously without stopping to change the opaque overlay. Use of the RapidCoater™ system has reduced the cost of laser peening by 30-40 percent and increased the process throughput by four to six times compared to conventional laser peening.

LSP Technologies, Inc. also recently commissioned the ManTech Laser Shock Peening Manufacturing Cell (LSPMC). The LSPMC features the latest generation laser peening system with a robust, production-hardened laser system. The 62.5 Watt, Nd:Phosphate glass laser operates at 1.25 Hz and emits a 50-Joule, 20 ns pulse. The laser will be upgraded to 2.5 Hz and 125 Watts in 2005. The 5.6 mm diameter laser beam spot will allow processing to occur at a rate of 4 square inches per minute. A picture of the laser is shown in Figure 2.

The ManTech laser system incorporates many design improvements, which have increased process throughput and boosted the reliability and maintainability of the system. The combined use of the RapidCoater™ system and the LSPMC has reduced the cost of laser peening by 50-75 percent and increased the process throughput by six to nine times compared to conventional laser peening.

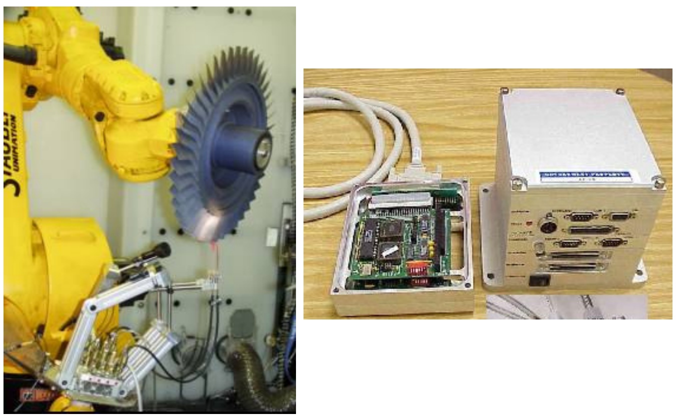


Figure 1. RapidCoater™ system set up for processing an F119 Integrally Bladed Rotor (left) with a dedicated computerized control module (right).

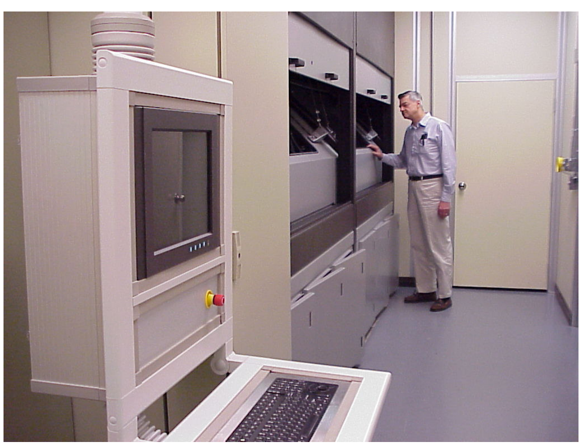


Figure 2. ManTech laser peening system featuring high rate processing with robust, production hardened equipment.

F119 IBR LASER PEENING PRODUCTION AT LSP TECHNOLOGIES

LSP Technologies is currently laser peening the airfoils on the Pratt and Whitney F119, 4th stage IBR that is flown on the F/A-22 Raptor aircraft. Implementation of laser peening increased the notched fatigue strength of IBR airfoils above the 55 ksi fatigue strength design criteria. A graph that illustrates the improvement is shown in Figure 3. The application of laser peening to the F119 IBR has reduced maintenance costs and eliminated the need for a costly redesign, estimated to be greater than $10M.

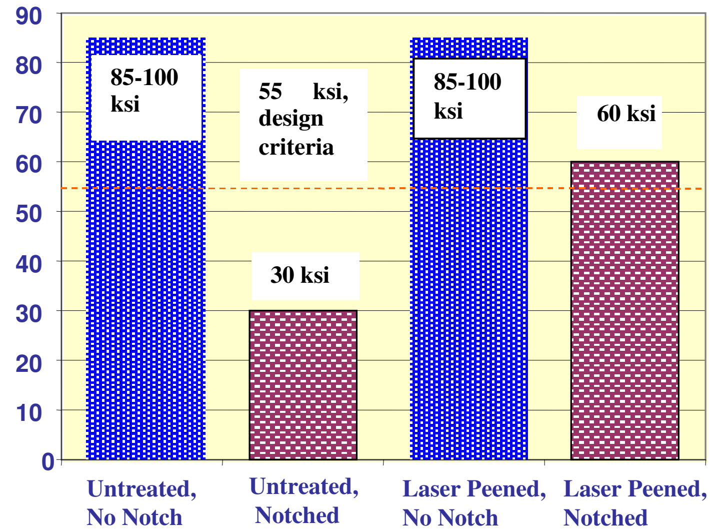


Figure 3. The effect of laser peening on F119 IBR fatigue life. A 0.050-inches deep EDM notch was used on the notched airfoils.

LASER PEENING FOR INCREASED FRETTING FATIGUE LIFE

Fretting fatigue is a problem associated with the function of many mechanical systems where there is metal-to-metal contact under vibrating load conditions. This is particularly true in some aircraft engine components such as the contact surfaces between the dovetail attachments of the engine airfoils or blades and the slots in which they are seated in the rotating disks. Laser peening has the potential to enhance the resistance of these fretting surfaces to failure by fretting fatigue.

Ti-6Al-4V fretting fatigue bars were subjected to fretting fatigue conditions consisting of fretting concurrent with fatigue cycling. The fatigue lives of the laser peened specimens were then compared to the lives of non-laser peened specimens of the same material tested under the same conditions. After fatigue and fretting testing, selected specimens were examined metallographically.

The material used was Ti-6Al-4V forged plate. The specimen configuration, developed in the Purdue Fatigue Laboratory [1,2], is shown in Figure 4. The specimen design was intended to simulate the fretting contact occurring in blade/dovetail during operation of an aircraft engine. The contact between the fatigue bar and the pad consists of a flat on the pad bearing on the flat surface of the fatigue bar. The 0.120-inch flat with the 0.120-inch blending radii were representative of engine hardware.

The central portion of the gauge length of all of the fatigue specimens and the flat contact area of several of the pads were laser peened, as shown in Figure 4. The fatigue bars were laser peened with large spots 5.6 mm in diameter, with the exception of one bar laser peened with small spots. All of the laser peened pad contact areas were peened with small spots. The

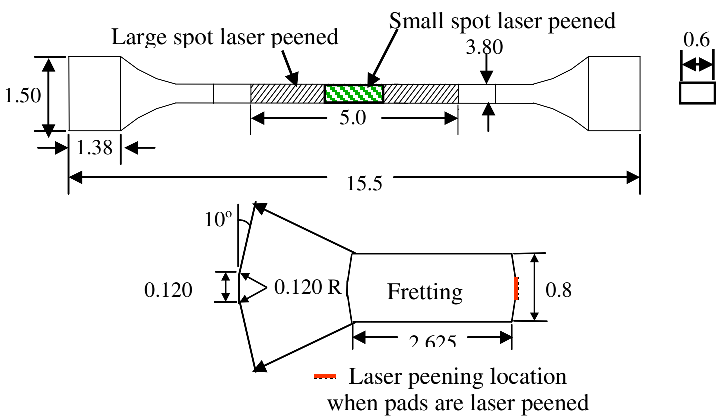
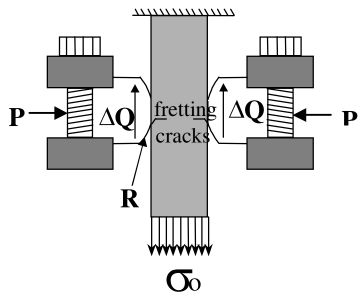


Figure 4. Fretting fatigue specimens and pads showing the laser peened areas. Dimensions are in inches.

relative intensity of the laser peening conditions for the fatigue bars and pads ranged from intermediate to high intensity.

The fretting fatigue tests were conducted at the Purdue University Fatigue Laboratory. A schematic of the setup is shown in Figure 5. The fatigue bar is vertical and is cyclically loaded from the bottom. A fretting pad on either side of the fatigue bar is pressed against it with a pressure, P, generating a cyclic shear load, Q, between the contacting surfaces of the fatigue bar and pads as the fatigue specimen lengthens and contracts under the cyclic load. A complete description of the testing setup can be found in Murthy, et.al. [2].



$$2\Delta Q = F_o - F$$

Figure 5. Schematic of the fretting fatigue test set up, from [3].

After fatigue testing, the fretted surfaces and metallographic sections of selected fatigue bars and the contact surfaces of selected fretting pads were examined by optical and scanning electron microscopy (SEM).

RESIDUAL STRESS

The fatigue bars and pads were laser peened with both the large and small spots at intermediate and high intensities. The compressive residual stresses are shown in Figure 6. The large spot, high intensity laser peening condition gave a surface stress of 810 MPa (117 ksi) and a compressive stress depth greater than 1 mm. The small spot laser peening condition gave a surface stress of 675 MPa (98 ksi) with a depth comparable to the large spot, high intensity laser peening condition. The residual stress profile for the high intensity, small spot laser peening condition, was not measured, but it would be expected to have a higher surface residual stress than

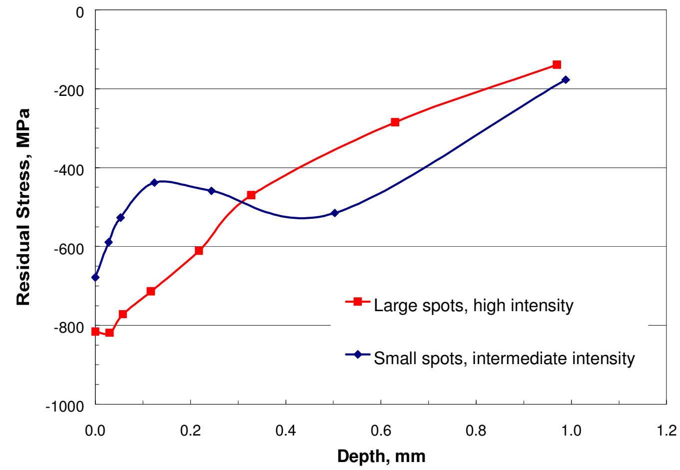


Figure 6. Residual stress profiles for the large spot and small spot laser peening conditions used for the fretting fatigue tests.

the intermediate intensity condition with equivalent or deeper residual stress.

FRETTING FATIGUE

Three fretting fatigue testing stress levels, S1 to S3, were used, representing increasing severity of fretting and fatigue conditions[4]. The pad contact stresses were 55 ksi, 75 ksi and 79 ksi respectively. The fretting fatigue results are shown in Figure 7. The fretting fatigue results show that at high intensity laser peening, both large spot and small spot laser peening were very effective, with runouts at the two highest stress levels.

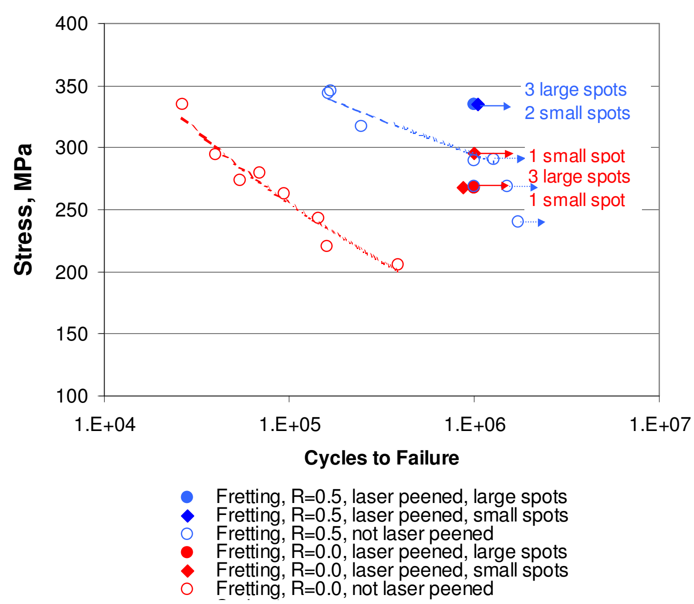


Figure 7. Increased fretting fatigue life after laser peening of Ti-6Al-4V.

Fretting fatigue stress level S3 was selected as the most severe level at which the testing machine could be operated. At this stress level laser peening increased the fretting fatigue life by at least 25 times compared to the outer bound of the non-laser peened fretting fatigue lives, with still further increases possible at higher stress levels. The intermediate laser peening intensity was still sufficient to increase fretting fatigue life to nearly $9x10^5$ cycles at S2, nearly 20 times increase in life. Two of the fatigue bars were used for two successive fretting tests, the first at stress level S1, and the second at stress level S2. All of these tests were runouts, indicating that the fretting cracks present from the first test run to a million cycles, did not propagate to failure in the second million cycles either, giving further evidence that laser peening significantly reduces the initiation and propagation of fatigue cracks from the fretting cracks.

Metallographic examination of the specimens showed that fretting cracks were present in the laser peened surfaces. Figure 8 shows fretting cracks in a laser peened surface of a fatigue bar tested at the S2 level to runout. These cracks did not propagate, although in the untreated condition, the bar would have failed at $8\ x10^4$ cycles. It appeared that laser peening did not have a discernable effect on the formation of fretting cracks. Just below the fretting contact surface, the contact and shear stresses dominate the compressive residual stress. However, as shown in Figure 7, the compressive residual stress was very effective in inhibiting the initiation of fatigue cracks from the fretting cracks, and it is the initiation of fatigue cracks from the fretting cracks, that leads to failure that so dramatically reduces the fretting fatigue life.

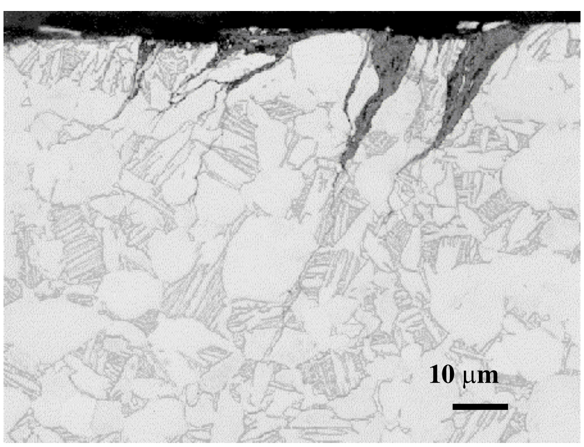


Figure 8. Fretting cracks at the trailing edge of the contact surface on fretting fatigue bar tested to runout at fretting fatigue stress level S2.

Conclusions

Laser peening has shown tremendous benefits for increasing the fretting fatigue life of Ti-6Al-4V. Improvements of more than 10 to 25-fold in life are possible after laser peening with either large spot or small spot patterns. The fretting behavior does not appear to be much affected by laser peening, the great benefit of laser peening arises from the inability of fatigue cracks to initiate and propagate from the fretting cracks. After initiation of a fatigue crack from a fretting crack, it would be expected that the initial growth rate of the fatigue crack would be slowed until it had propagated some distance through the compressive stress field. These are the primary reasons that laser peening is so effective in increasing fretting fatigue

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the USAF Materials and Manufacturing Directorate under contract F33615-98-C-5150 and Navair under contract N68335-01-C-0320 for their support of the program.

REFERENCES

1. Szolwinski, M.P.and Farris, T.N.,"Observation, Analysis and Prediction of Fretting Fatigue in 2024-T351 Aluminum Alloy", Wear, Vol. 221,pp.24-36 (1998)
2. McVeigh, P.A., Harrish, G., Farris, T.N., Szolwinski, J.P., "Modeling Interfacial Conditions in Nominally Flat contacts for Application to Fretting Fatigue of Turbine Engine Components",
3. Murthy, H., Rajeev, P.T., Farris, T.N. and Slavik, D.C.,"Fretting Fatigue of Ti-tAl-4V Subjected to Blade/Disk contact Loading", Developments in Fracture Mechanics for the New Century, 50th Anniversary of Japan Society of Materials Science, Osaka, May, 2001, pp. 41-48 (2001)
4. Clauer, A.H. and Sokol, D.W., to be published.