# Lifetime enhancement of propulsion shafts against corrosion-fatigue by laser peening*

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**ABSTRACT**

*This paper reports substantially enhanced fatigue and corrosion-fatigue lifetimes of propulsion shaft materials, 23284A steel and 23284A steel with In625 weld overlay cladding, as a result of shot or laser peening. Glass reinforced plastic (GRP) coatings and Inconel claddings are used to protect shafts against general corrosion and corrosion pitting. However salt water leakage penetrating under a GRP can actually enhance pitting leading to crack initiation and growth. Fatigue coupons, untreated and with shot or laser peening were tested, including with simultaneous salt water immersion. Controlled corrosion of the surfaces was simulated with electric discharge machining (EDM) of deep pits enabling evaluation of fatigue and corrosion-fatigue lifetimes. Results specifically show high energy laser peening (HELP) to be a superior solution, improving corrosion-fatigue resistance of shaft and cladding metal, reducing the potential for corrosion pits to initiate fatigue cracks and dramatically slowing crack growth rates. At a heavy loading of 110% of yield stress and with 0.020 inch deep pits, laser peening increased fatigue life of the steel by 1370% and by 350% in the corrosion-fatigue testing.*

**KEY WORDS**

Propulsion shafts, laser peening, shot peening, fatigue life, corrosion, corrosion-fatigue, pitting.

**INTRODUCTION**

Prevention of corrosion-induced fatigue cracking of propulsion shafting is an important operational and safety requirement and thereby significantly impacts the construction and operational cost of ships. The issue is specifically important for submarines where viability of shafts specifically defines operations limits.

In ship operation shafts undergo heavy mechanical loading while simultaneously exposed to the salt water environment. Shafts are often fabricated using weld-overlay Inconel coatings and glass reinforced plastic (GRP) coatings to protect against corrosion and corrosion pitting. However salt water can seep under the coatings where the confined environment actually exacerbates corrosion pitting (crevice corrosion) leading to early fatigue crack initiation. Consequently ship inspection and overhaul schedules are often dictated in time to ensure shaft integrity. The issue is of particular importance to submarine safety.

As summarized by Jonart in his thesis, "Submarine propulsion shafts have demonstrated acceptable reliability performance when inspected and refurbished at least every 6 years (Jonart 2014) . Designers wish to extend the inspection interval to 12 years without sacrificing reliability. This interval is unprecedented, as no known submarine shafting system is currently operated with this inspection cycle, nor are any known commercial vessel shafts. Experience and improved design have eliminated many threats to the life of a submarine shaft, but inspections of existing shafts show a high percentage with signs of wetting, leaving designers with less-than-acceptable confidence to approve this longer inspection interval due to the possibility of corrosion-fatigue failure." Jonart's uses probabilistic models from literature for pitting and cracking of wetted shafts along with Monte Carlo simulations to predict expected times from shaft wetting to pitting, to crack initiation and growth and to eventual shaft failure. Based on allowable risk, this type of modeling is used to set allowable time intervals between shaft inspections. Reducing the potential for shaft failure would greatly enhance safety and could increase inspection intervals and thereby enable significant cost savings and increased ship availability.

In this work we evaluate fatigue lifetimes of 23284A steel, a steel used for propulsion shafts, alone and in the presence of simultaneous salt water exposure (corrosion-fatigue lifetimes). We also evaluate the fatigue and corrosion fatigue lifetimes of this steel when deployed with an Inconel 625 weld overlay, an overlay used to inhibit corrosion and corrosion pitting. The work focuses on the ability of shot and laser peening to extend the lifetimes with the intent to enhance safety and reduce shaft inspection and replacement intervals.

**PEENNG SURFCE TREATMENTS**

All peening processes have in general the characteristic that they plastically deform the surface layer of a component and due to the Poisson's expansion a combination of residual stress or strain result. Figure 1 illustrates this process for the case of laser peening, a process first demonstrated for metals at Battelle Labs in the 1970s (Fairand 1972). Development work was carried on through the 1990s (Clauer 2002, Fabbro 1990) followed by military (Thompson 1997) and then commercial applications (Curtiss-Wright 2013). Although laser peening generates an especially deep surface compression and resulting stress, the compression and transverse expansion reaction is applicable to all types of peening. In laser peening a thin (1mm) layer of deionized water is made to flow over a component to be peened. The laser light is made incident on the surface passing through the water layer and creating a plasma. In the case of high strength propulsion shaft steels, high irradiance laser light of typically 10 GW/cm$^2$ is used to create sufficient plasma pressure to yield the high strength material. Due to its incompressibility and the finite shock wave transit time through the water, the plasma volume is tamped, unable to expand during the lifetime of the plasma. The plasma is rapidly heated by the laser into the range of 13,000K and with the volume tamped by the water the pressure rises above the yield stress of the metal component. A shock wave thus propagates into the metal plastically compressing the material normal to the surface. The compressed metal attempts to transversely expand, pushing against the surrounding unpeened material thereby creating a local compressive field. The component reacts to this field and depending on its constraints and stiffness, residual stress and component strain result. In the case of shot peening the laser light and water are absent and high velocity metal or ceramic balls impact the surface creating cavitation peening, collapsing bubbles create mini-shape charges that plastically impact the surface.

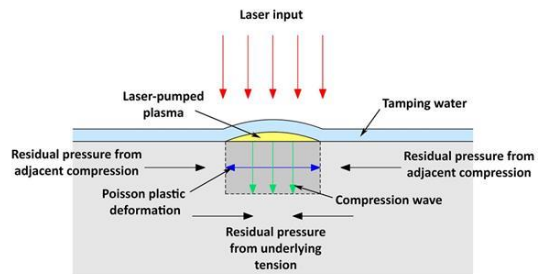


Figure 1. Peening processes work by plastically compressing material normal to a metal surface resulting in transverse expansion that builds stress and strain fields. Laser peening is illustrated in this example.

Peening processes can be distinguished by the depth of plastic deformation, the amount of surface hardening and cold work generated. Of particular interest is the depth of plastic deformation and thus compressive stress generated. Shot peening done with shot S330 shot typically generates indents of 0.01 inch (0.3 mm) size (kirk, 2010). The impact area is generally representative of the depth of plastic deformation and thus residual stress generated. In this work we distinguish high energy laser peening (HELP) with energy on target of 10 to 20 Joules per pulse from low energy laser peening where energies are typically in the range of 1 Joule per pulse or less (Sano 2000). Since the depth of plastic response is directly related to the footprint size, the high energy laser approach can generate the required shock wave pressure over footprint sizes of 3 mm to 1 cm on a side.

In contrast low energy laser peening is limited to sub-millimeter spot sizes. In the case of high strength steel high energy laser peening is typically done with 3 mm square spots, that is 0.12 inch size impacts and thus one expects plastic deformation and compressive stress to 3 to 5 mm depths as is typically observed. The contrast in depth of compressive stress between laser and shot peening is shown in Figure 2. The residual stress generated by the shot peening penetrates to approximately 0.010 inches (0.3 mm) whereas the laser peened material shows 10 times deeper compressive stress to 0.10 inch (2.5 mm) and actual plastic deformation to 0.20 inch (5 mm) depth. Deeper depths place the compressive layer well below the pitting termination depth and thus, as the data will show, allow significant enhancement against corrosion-fatigue failure.

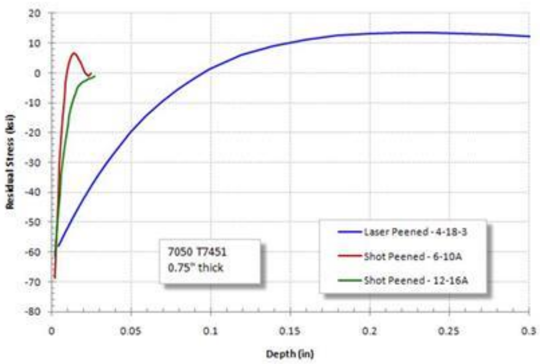


Figure 2 illustrates the contrast in compression depth generated by shot and laser peening. The residual stress generated by the shot peening penetrates to approximately 0.010 inches whereas the laser peened material shows compressive stress to 0.10 inch and actual plastic deformation to 0.20 inch depth.

**IMPACT OF CORROSION ON FATIGUE LIFE:**

Corrosion induced pitting can initiate and accelerate the rate of fatigue cracking. Chen and Kelly have developed predictions of the maximum size of a hemispherical pit in type 304 and 316 stainless steels after exposure to atmospheric conditions (Chen, 2010). The results of their calculations agree well with several sets of data for near-seacoast exposures on three continents for exposure times out to 26 years. Further evaluations have placed maximum pit size at around 0.2 mm (Woldemedhim, 2014). Thus we began this work with the realization that pitting can be the initiation source for fatigue cracking and an expectation that the deep stress of high energy laser peening will better protect from fatigue cracking.

Pitting often grows under the surface of a component and notoriously tends to trigger failures by fatigue or stress corrosion cracking. A pitting-potential model introduced in 1976 by Jose R. Galvele has had a major influence on the development of corrosion science Galvele 2010). The electro-chemistry of reactions, such as chloride ions, drive the pitting corrosion (Greene 1959, Kolotyrkin 1963, Szlarska 1971). The chlorine ion has been identified as the species which attacks or breaks down a protective film leading to localized dissolution.

Surface treatments such as shot peening, hammer peening, ultrasonic peening and laser peening generate compressive stress at various depths into a surface. However, as shown in the illustration of Figure 1, in any peened component tensile stress will appear as the response below the compressive layer. Thus the depth of compressive stress generated by the various treatments combined with component geometry is a critically important consideration in a corrosion application. Pitting that penetrates beneath the compressive layer can accelerate crack initiation as discussed in Woldemedhim et al (Woldemedhim 2014) and thus accelerate fatigue failure.

**TEST PLAN AND METHOIDOLOGY**

In order to test the effectiveness of both shot peening and high energy laser peening to extend the lifetime of shaft material we planned a series for fatigue and corrosion-fatigue tests comparing the treated samples to ones that were unpeened.

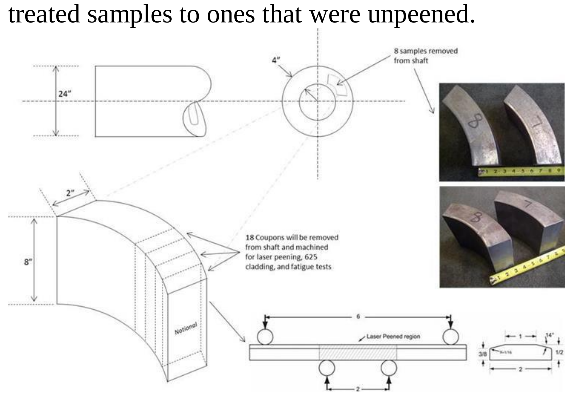


Figure 3. 23284A steel from Los Angeles class submarine used for here to make the propulsion shaft fatigue and corrosion-fatigue test coupons.

Toward this end, we fabricated two types of 4-point bend samples: samples of 23284A steel only and samples of 23284A steel with In625 weld overlay. The samples were fabricated, as shown in Figure 3, of material from a Los Angeles Class SSN 688 submarine shaft with strength corresponding to 90 ksi yield stress. The 23284A material and In725 weld overlay coatings were provided by the Applied Research of Penn State University.

Figure 4 shows photos and dimensions of the two sample types. Samples were designed in a 4-point bend configuration to best replicate the loading imposed on a submarine shaft in operation. We wanted to impose, as best as possible, the stress riser effects of corrosion pits of controlled depth; to best do o we electro-discharge machined 1 mm diameter by 0.5 mm deep “pits” into specific samples. We estimated a stress intensity factor of approximately two (2) introduced by these “pits”.

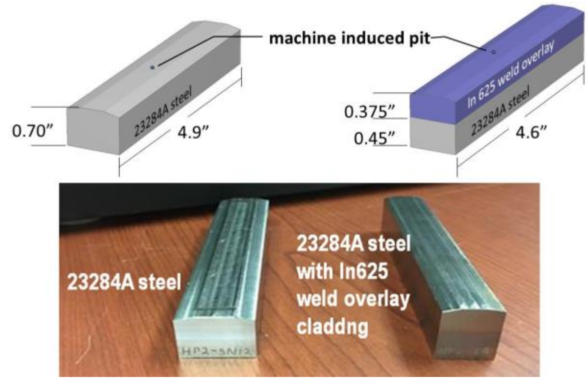


Figure 4. Fatigue test samples of 23284A steel and 23284A steel with In718 weld overlay. A round notch of 1 mm diameter and 0.5 mm depth was EDM cut into chosen samples to simulate in a controlled manner the stress riser associated with a corrosion pitting.

**STRESS MEASUREMENTS AND ANALYIS**

To evaluate the potential of peening to enhance the fatigue performance of the coupons, a selected number were shot and laser peened. The shot peened coupons were treated at 8 to 12 Almen intensity 230R shot with 100% coverage. The laser treated coupons 23284A steel were peened at an irradiance of 10

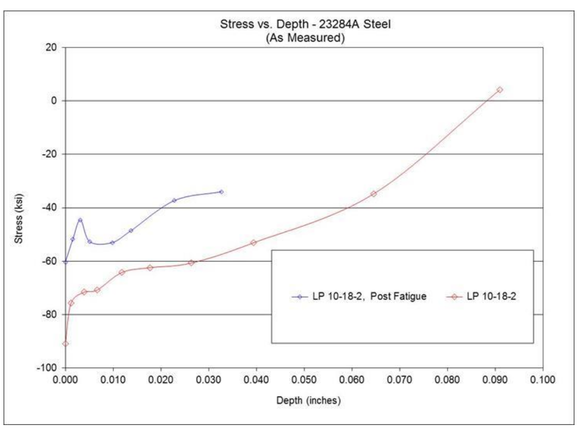


Figure 5. X-ray diffraction measurements of stress vs. depth for samples of 23284A steel after 2 layers of laser peening. Notation 10--18-2 represents laser irradiance of 10 GW/cm2, 18 ns pulse duration and 2 peening layers.

GW/cm2 with 18 ns pulses, and aluminum ablation layer tape. A test sample was measured for stress vs. depth using a slitting (crack compliance) technique with results shown in Figure 5. As can be seen, the laser peening induces a strong surface stress of 80 ki (560 MPa) comparable to the 90 ksi (630 MPa) yield stress of the material. Most significantly the laser peening stress reaches to a very deep 0.090 inch depth, a factor that provides the best protection against crack propagation. We also measured residual stress after the fatigue testing was complete. The figure shows about 20% loss but still a highly useful 60 ksi compressive stress.

Residual stress measurements were also made of the samples which had the In625 weld overlay applied. Figure 6 shows results from x-ray diffraction made as deep at 0.080 inches (2 mm) depth. The surface stress is seen to be about 100 ksi (700 MPa) and again a deep depth, in this case of 0.09 inches (2.25 mm). There was some concern about high tensile stress generated in the In625 by the welding overlay process and how it would react to the laser peening. We evaluated an unpeened sample again using XRD and found the sample to have been well annealed, with essentially no tensile stress.

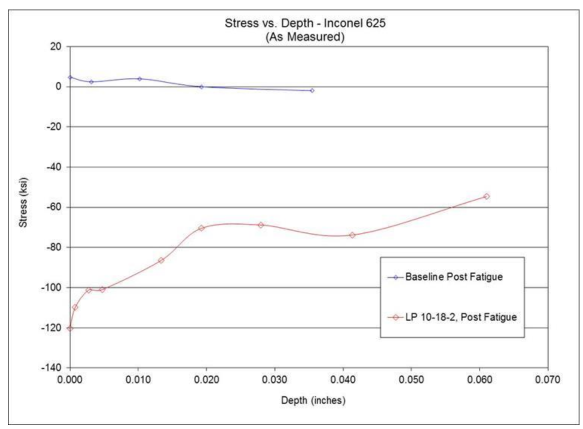


Figure 6. X-ray diffraction measurements of baseline and laser peening stress in In625.

Finite element analysis (FEA) was performed to estimate the stress level and distribution generated by the mechanical test loading within the loaded coupon. Figure 7 shows the finite element mesh and the pre-dicted FEA stress profile of the loaded coupon. CWST applied strain gauges to a first unclad fatigue test coupon and loaded it in the Instron 20 fatigue test rig. Figure 8 shows the fatigue test rig with coupon loaded (note that the coupon is loaded in an inverted orientation compared to that shown in Figure 7). The reactive load is provided by the rollers at both left and right below the test coupon. The instrument in the foreground is a microscope with digital camera output; CWST observes and video records cracks developing during the testing which allows back tracking on the video to determine cycle count at which cracking initiated. Crack growth rate vs. applied cycles is also recorded. The initial test coupon was loaded to a level just where the strain vs. load level response became non-linear. From this the yield load value of the 23284A coupon was determined to be between 9000 and 10,000 lbs equating to a yield stress ($Y_s$) 87 to 97 ksi stress using values for Young's modulus of E=29E6 and Poisson ratio of 0.3. This indicates that the 23284A material is a Class 2 material.

## FATIGUE AND CORROSION-FATIGUE TESTING

With the calibration complete a coupon with no machined pit was loaded into our 20 kip fatigue test rig as shown in Figure 9 and cycled at a stress level of $0.8s_y$, equating to 78 ksi. The coupon cycled for 2 million cycles without failure. Because this could be a runout condition where the coupon would not fail, the load was increased to generate a stress of 122 ksi and further testing performed specifically to obtain a baseline result in the range of 500,000 cycles for an untreated coupon without machined pit.

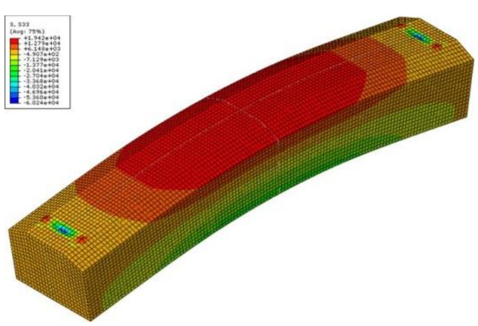

Figure 7. Finite element prediction of stress distribution in loaded 23284A test coupon.

The test plan included fatigue cycling both bare 23284A steel and In625 weld-overlay clad coupons of similar configuration. The plan included unpeened, shot peened and laser peened coupons using straight fatigue and corrosion-fatigue testing. In both cases coupons with no induced pit were tested as baseline representing the new-condition propulsion shafts. Then in order to test in a controlled manner the fatigue life debit resulting from the formation of a corrosion pit we electro-discharge machined a 1 mm diameter by 0.5 mm deep "pit" in to selected coupons. The rational for EDM was that it would generate a repeatable stress riser in each coupon as compared to the more stochastic nature of the position and depth a corrosive pit.

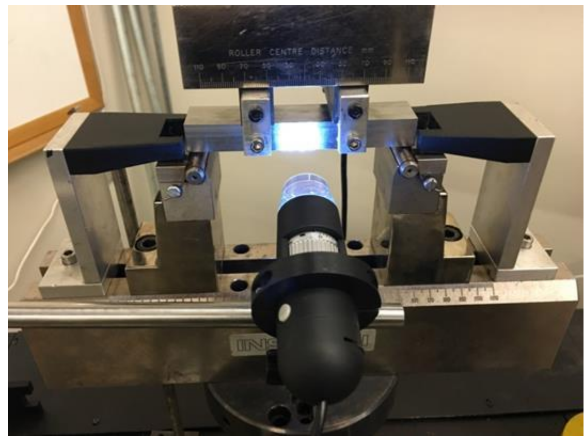

Figure 9. Instron 20 kip fatigue test rig in 4-point bend configuration for testing.

Each of the bare and weld-overlay coupons were tested with a machined-in pit. This test provided the data on fatigue life debit resulting from the formation of a corrosion pit in the shaft. In further tests coupons were either laser peened or shot peened and then pitted to show the respective benefit of each of these processes to prevent severe cracking should a corrosion pit form during ship operation.

A test coupon of 23284A material with In625 weld overlay cladding but no EDM-pit was initially tested at 83 ksi loading based on expected yield stress between 60 -90 ksi. The coupon ran and was stopped at 2.3 million cycles without failure and was then EDM pitted and run for another 516,861 cycles again without failure. It was then uploaded to 91.3 ksi loading (nominal loading of the smooth coupon excluding the stress riser associated with the pit) and failed at 27,987 cycles. As shown in Figure 10 a second EDM-pitted In625 clad coupon was run at 91.3 ksi loading and failed after 337,116 cycles. This result was used as the baseline for comparative testing of laser peening and shot peening of the In625 material.

A shot peened then EDM-pitted coupon was run at 91.3 ksi and failed after 482,000 cycles thus providing a 40% improvement over the untreated coupon.

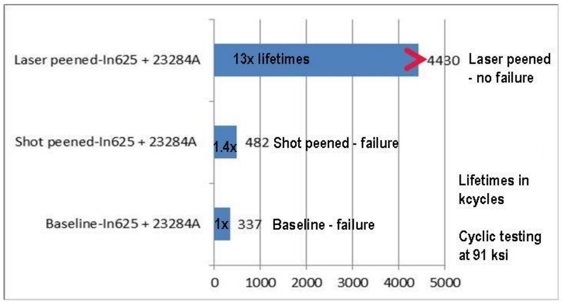


Figure 10. Laser peening dramatically improves the fatigue lifetime of 23284A + In625 weld overlay cladding with 500 micron deep pit.

Much more positively, a coupon was laser peened then EDM-pitted and cycled for 4,430,444 cycles without failing. This represents a lifetime improvement for laser peening of the In625 cladded material of in excess of 1300%. We recognize the limited testing and thus statistics of the testing but do point out the large improvement of the laser peening which is well beyond expected statistical variations.

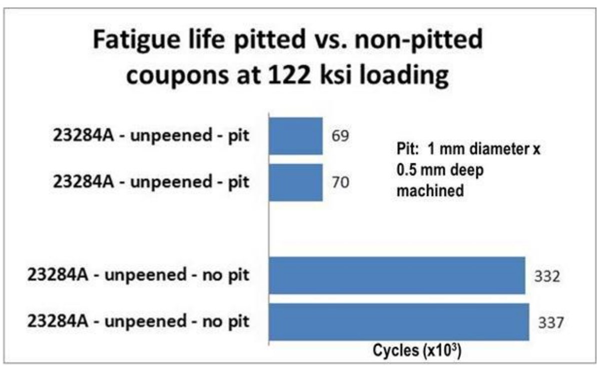


Figure 11. Induced pit of 500 micron depth reduces fatigue life of bare 23284A shaft material by 4.8X

Next 23284A coupons without cladding were tested at 122 ksi load and 7Hz rate. In two separate tests coupons failed respectively at 332,000 and 337,000 cycles. This load was approximately 125% of yield stress, a stress not normally experienced by a propulsion shaft in operation but one initially selected to ensure failure of the baseline coupon within reasonable testing times. Identical steel coupons with an EDM pit were tested at the 122 ksi load and failed at 69,000 and 70,000 cycles showing as expected that the formation of a pit will decrease the lifetime, in this case by a factor of 4.8 times at this high stress level.

Shot peened coupons were then prepared, EDM pitted and tested giving lifetimes of 73,000 and 59,000 cycles, basically indicating minimal lifetime improvement for shot peening of a pitted coupon. Coupons of the 23284A steel were laser peened, EDM pitted and tested giving lifetimes of 135,000 and 141,000 cycles, that is, a factor of 2 times improvement at this high stress level for laser peening over both baseline and shot peen coupons. These test results are graphically shown in Figure 12.

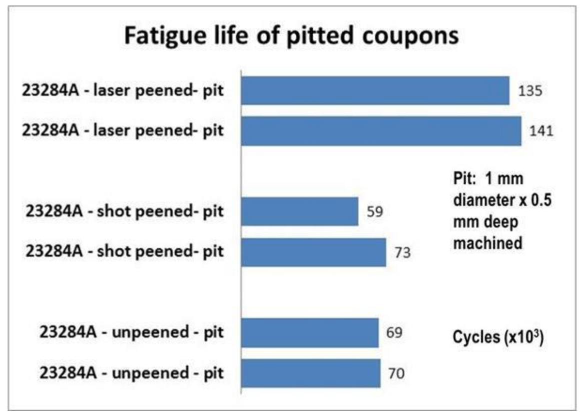


Figure 12. Relative fatigue life of 23284A pitted coupons that were unpeened, shot peened or laser peened. Laser peening doubled the life of the pitted coupon at 125% of yield.

In order to test coupons at a stress level closer to that experienced in operation the load level for the unclad coupons was reduced by 15 ksi generating a stress reduction to 107 ksi. EDM-pitted coupons in the unpeened, shot and laser peened conditions were tested. As expected reducing the test stress loading increased lifetimes. The unpeened and EDM-pitted coupon lifetime increased to 580,000, an 800% increase for the 12% reduction in load stress. The EDM-pitted and shot peened increased coupon ran to 1,564,000 cycles and the EDM-pitted laser peened coupon impressively ran to 7,968,000 cycles where it was stopped without failure, an increase of greater than 1370% above the new baseline. Figure 13 summarizes the results. At present, this coupon has not failed but has been removed from test and set aside pending further interest in testing. It can be put back on the fatigue test rig for continued testing at a later date.

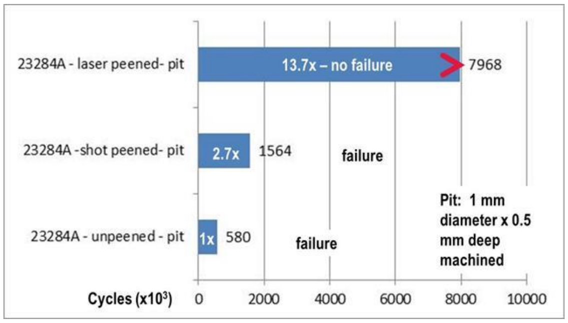


Figure 13. Reducing stress level to 107 ksi (110% of yield stress) increased the baseline pitted coupon fatigue life to achieve 580,000 cycles. At this reduced level the shot peened and pitted coupon ran 270% longer. The laser peened coupon did not fail after 7,968,000 cycles an increase of 1370%.

An additional set of tests evaluated simultaneous corrosion in salt water with fatigue. For this testing, we constructed a salt water immersion tank around the 4-point bend test fixture so that the coupons could be simultaneously tested for both fatigue crack growth and corrosion induced crack growth.

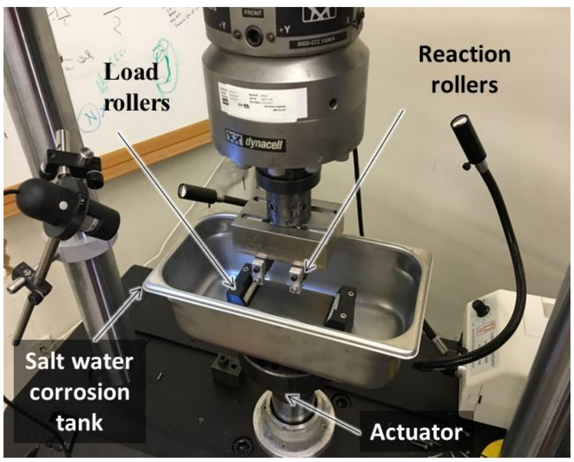


Figure 14. Corrosion-fatigue test setup with stainless steel tank for simultaneous testing of fatigue and salt water immersion.

In the corrosion-fatigue tests, two coupons were tested with induced pits and no peening to serve as baseline for an untreated shaft. Two additional coupons were laser peened and then had a pit induced in each followed by the corrosion-fatigue testing. Finally two coupons were shot peened, pits induced and corrosion fatigue tested. Figure 15 shows the results of these tests where it can be seen that the laser peening overcomes the pit and corrosion lifetime debit by 350%

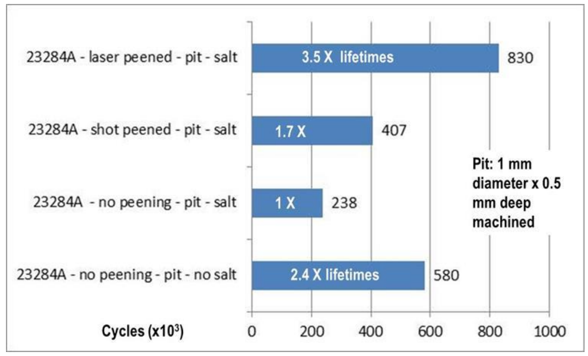


Figure 15. Tested at 110% of yield stress, coupons show a 240% drop in lifetime when exposed to salt water corrosion. However laser peening overcomes this debit and actually increases the lifetime associated with corrosion exposure by 350%.

It is clear how aggressive the corrosion fatigue is and how it can dominate the overall lifetime. Figure 16 shows a corrosion-fatigue sample that was laser peened. The peening successfully arrested cracking at the pit (small round white spot) and the eventual failure resulted from corrosion pitting induced at the two break points of the 4-point bend bar. Again the laser peening enabled 350% lifetime improvement.

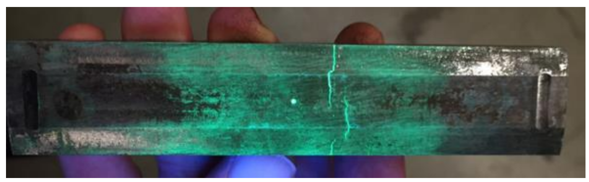

Figure 16. Corrosion-fatigue testing demonstrates the dominance of corrosion –induced cracking to lifetime. Laser peening of 23284A propulsion shaft steel sample does not fail at induced pit but eventually fails due to corrosion initiation.

## SUMMARY

Using fatigue and corrosion fatigue testing, we have investigated the potential of laser and shot peening to extend the lifetime of propulsion shaft material, including 23284A steel and steel with In625 weld overlay. In all cases the tests showed that laser peening significantly increases the lifetime of the shaft material and the weld-overlayed material beyond that of untreated or shot peened material. For 23284A material clad with In625, material less prone to corrosion induced pitting, the laser peening increased the lifetime of a notched sample by over 1300% without a failure occurring.

For the bare 23284A steel test results are summarized in Figure 17. Propulsion shaft material experiences a 480% loss of fatigue lifetime at 125% of yield stress, following the EDM of a 1 mm diameter by 0.5 micron pit intended to simulate a salt water induced corrosion pit,. In contrast laser peening doubles the lifetime of pitted material at this high stress level. Pitting combined with salt water exposure dropped the fatigue performance by more than 5 times. Laser peening overcomes much of this deficit, improving corrosion-fatigue by 350%.

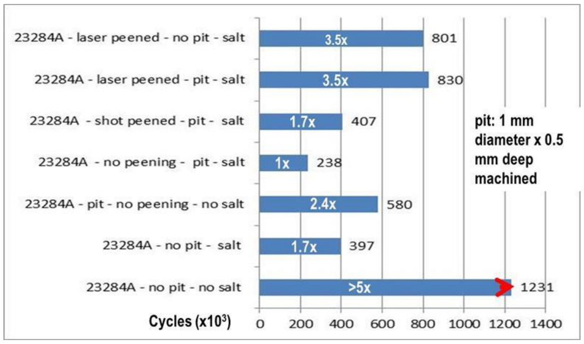


Figure 17. Laser peeing of 23284a propulsion shaft steel increases fatigue and corrosion-fatigue life by a factor of 350%.

Inspection intervals, driven by concern for corrosion-fatigue failure, are a major are a major driver in ship overhaul and hence a driver of cost and ship availability. Laser peening could safely extend inspection intervals.

## REFERENCES

CHEN, Z.Y., and Kelly, R.G., Computational Modeling of Bounding Conditions for Pit Size on Stainless Steel in Atmospheric Environments, Journal of the Electrochemical Society, **157**(2), C69-C78, 2010.

CLAUER, A. H. "A Historical Perspective on Laser Shock Peening". *Metal Finishing News*. **10**

Curtiss-Wright http://www.curtisswright.com/news/press-releases/news-release-details/2013/Curtiss-Wright-Awarded-Contract-From-Rolls-Royce/default.aspx

FABBRO, R.; Fournier, J.; Ballard, P.; Devaux, D.; Virmont, J. (1990). "Physical Study of Laser Produced Plasma in Confined Geometry". *Journal of Applied Physics*. **68** (2): 775.

FAIRAND, B. P. (1972). "Laser Shock-Induced Microstructural and Mechanical Property Changes in 7075 Aluminum". Journal of Applied Physics **43** (9):3893.

GALVELEe, J. R., Transport Processes and the mechanism of Pitting of Metals, J. Electrochem. Soc., **Vol. 123**, 464.

GREENE, N. D., and Fontanta, M. G., Corrosion, **Vol. 15**, pp. 41, 1959.

JONART, D.E., (2014). Submarine Propulsion Shaft Life: Probabilistic Prediction and Extension through Prevention of Water Ingress, https://dspace.mit.edu/handle /1721.1/92083.

KIRK, D., Peening Indent Dimensions, The Shot Peener, 24-32, Summer 2010.

KOLOTYKIN, J.H., Corrosion, **Vol. 19**, pp. 261, 1963

SANO, Y.; Kimura, M.; Sato, K.; Obata, M. et al, Proc. 8th Int. Conf. on Nuclear Eng., (ICONE-8), Baltimore, 2000.

SZLARSKA-SMIALOWSKA, Z., Corrosion, **Vol. 27**, pp. 223, 1971.

THOMPSON, S. D.; See, D. E.; Lykins, C. D. and Sampson, P. G. in *Surface Performance of Titanium*, J. K. Gregory, H. J. Rack and D. Eylon (Eds.), The Minerals, Metals &Materials Society, pp. 239–251, 1997.

WOLDEMEDHIM, M.T., Shedd, M.E., and Kelly, R.G., Evaluation of the Maximum Pit Size Model on Stainless Steels under Thin film Electrolyte Conditions, Journal of the Electrochemical Society, **161**(8), E3216-E3224, 2014. .

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