SHOT PEENING IN STEAM TURBINES

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ABSTRACT
Shot peening has been used for centuries to improve the fatigue life in many metals, and in modern applications (1920's), began with shot peening automobile engine valve springs. Since then the practice of shot peening has been used in many other products. This includes aircraft airframes and engines, Diesel engines, automobile crank shafts and gear teeth, marine reduction gears, automobile and truck parts, railroad car and engine parts, elevators and other lifting equipment, as well as many other mechanisms subjected to fatigue. Steam turbines designed by virtually all turbine manufacturers use shot peening and/or compression rollers to enhance fatigue life. More recently, shot peening has been used to improve metal life subjected to stress corrosion cracking (SCC), and intergranular attack (IGA).

In the last twenty-five years, shot peening has been used to combat corrosion fatigue (CF) in conjunction with the use of corrosion resistant coatings in steam turbine blading operating in corrosive, wet steam environments. Also, coatings have been given consideration after shot peening to further improve SCC resistance in steam turbine rotor discs, but use was deferred when field application became a necessity. To date, shot peened and coated blading, with the coating intact, has performed without failure, but the period of service (about 15 years) is considered too short to project success for the entire design life of the part because it is operating in a pitting inductive wet steam environment.

This paper will discuss the benefits of shot peening steam path parts for steam turbines used in fossil fuel, nuclear, and geothermal service. It will suggest the possible benefits of shot peening welded parts subjected to elevated temperature service, and confirm the benefits of in-situ shot peening to achieve a limited life improvement in a nuclear steam turbine repair. It will also discuss the role the operating environment may have in limiting the life of shot peened parts.

INTRODUCTION
Steam turbines are used for numerous applications in converting the heat energy in expanding steam, producing electric power by driving a generator, pumping force by driving a pump, and motive force by turning a ship's propeller, to name a few of the most popular uses. The stresses created by the steam pressure, centrifugal forces caused by the spinning of the bladed rotor, and the unavoidable vibration resulting in the blading make shot peening an attractive tool to increase the margin between failure and success to an impressive degree.

Shot peening has been used in steam turbines for at least the last 50 years, first appearing in locations where fatigue and corrosion fatigue were taking their toll. Thus shot peening of tenon holes in bucket covers, on blade serrated root radii, and tie wire holes in blade foils, were among the earliest applications used by the blade manufacturers to improve the fatigue life of the parts.

In the past 30 years, there has been increased use of shot peening, not just as a fatigue life enhancement, but for other reasons, to be discussed later, and sometimes applied in the field at the request of the owner of the turbines, rather than by the turbine manufacturer. These experiences will be covered in more detail as they are the basis for a significant increase in the scope of possible benefits to be derived from the shot peening process.

BACKGROUND

In the world of technology, the steam turbine out dates shot peening by many centuries, but gradual use of shot peening in steam turbines has increased steadily. It is believed that shot peening was used in reduction gears before turbines, but it is generally agreed that shot peening was first used in steam turbines as a means for increasing the margin of success in dealing with fatigue cracking in a failing design. Subsequent success then generated the standard practice of shot peening these locations, such as tenon holes in covers. This led to shot peening other locations of high vibratory stress, such as tenons and tie wire holes. Today there are a very large number of steam turbines which would not survive i.e., avoid premature failure, if it were not for the benefits resulting from shot peening. Many people think of steam turbines as machinery that runs too hot to benefit from shot peening. But later in the paper, an approach will be presented which is expected to verify that shot peening can be beneficial in elevated temperature service as well as in service below 700° F (371° C).

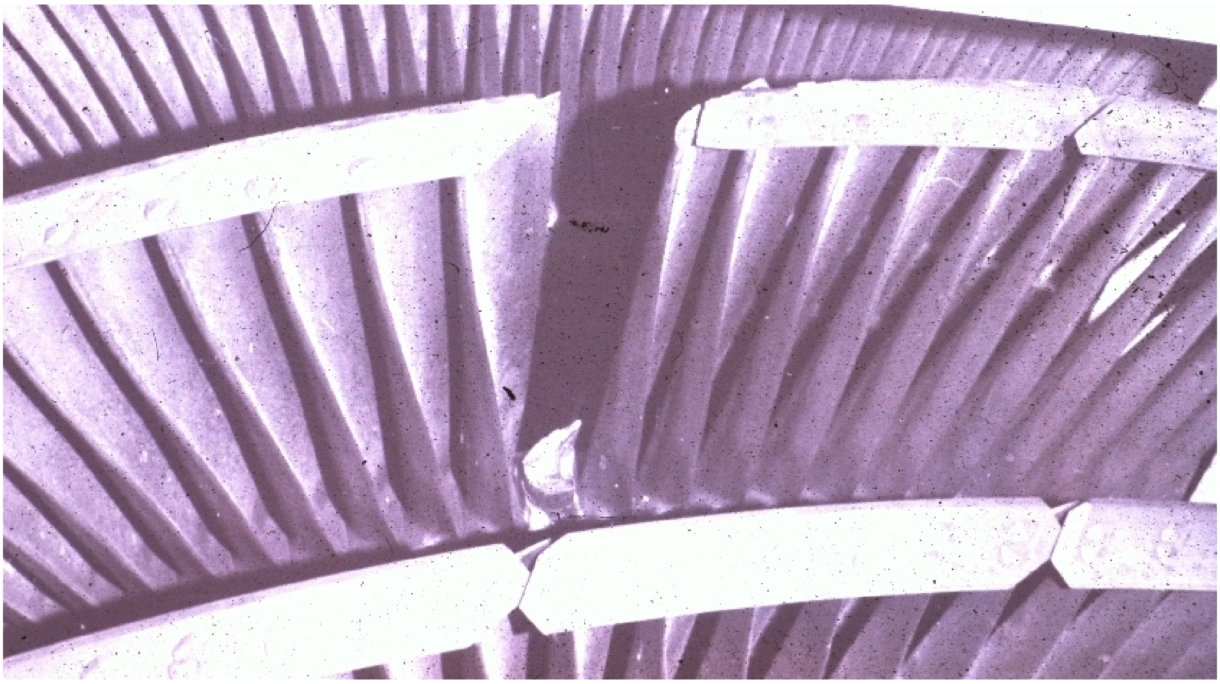
As noted above, shot peening came into use in steam turbines as a way to improve the fatigue strength of the material. Enhancements which reduce the risk of corrosion fatigue (CF), stress corrosion cracking (SCC), and other alternating and steady stress related failures, are welcome in the machine design world as valuable tools, especially when dealing with an operating environment that is aggressive or unpredictable. Over the years shot peening has been applied to a variety of metals to improve fatigue characteristics, and with the advent of SEM (Scanning Electron Microscope) technology, failure mechanisms such a SCC and Intergranular Attack (IGA) have been identified[1]. Shot peening has proven to retard SCC and eliminate IGA. Thus it is not surprising to find shot peening in the REQUIRED SERVICES category on highly stressed turbine parts.

DISCUSSION

CASE HISTORIES

790 MW L-2 Stage Rotor Blade Failures

In 1973, and again in 1975, an electric power company suffered a forced outage on a large 790 mw coal fired plant low pressure steam turbine when rotor blades in the same L-2 stage broke off near the base of the blade [2, 3].



In the 1973 failure, one blade broke off. Subsequent examination also revealed cracks in the covers and tenons on numerous blades. In the initial repair, it was decided to dress out the tenon cracks because they turned out to be shallow. New covers were made and foxholed to accept the shorter tenons resulting from the cover removal work. Both the tenon holes in the covers and the base of the tenons were shot peened to increase their resistance to fatigue. (Improvement summarized- with the exception of the increased local fatigue strength due to shotpeening, there was none. In fact, the tenons had been weakened by loss of section modulus when the cracks were ground out, and the covers were weakened by a reduced section-modulus due to the foxholing required.)

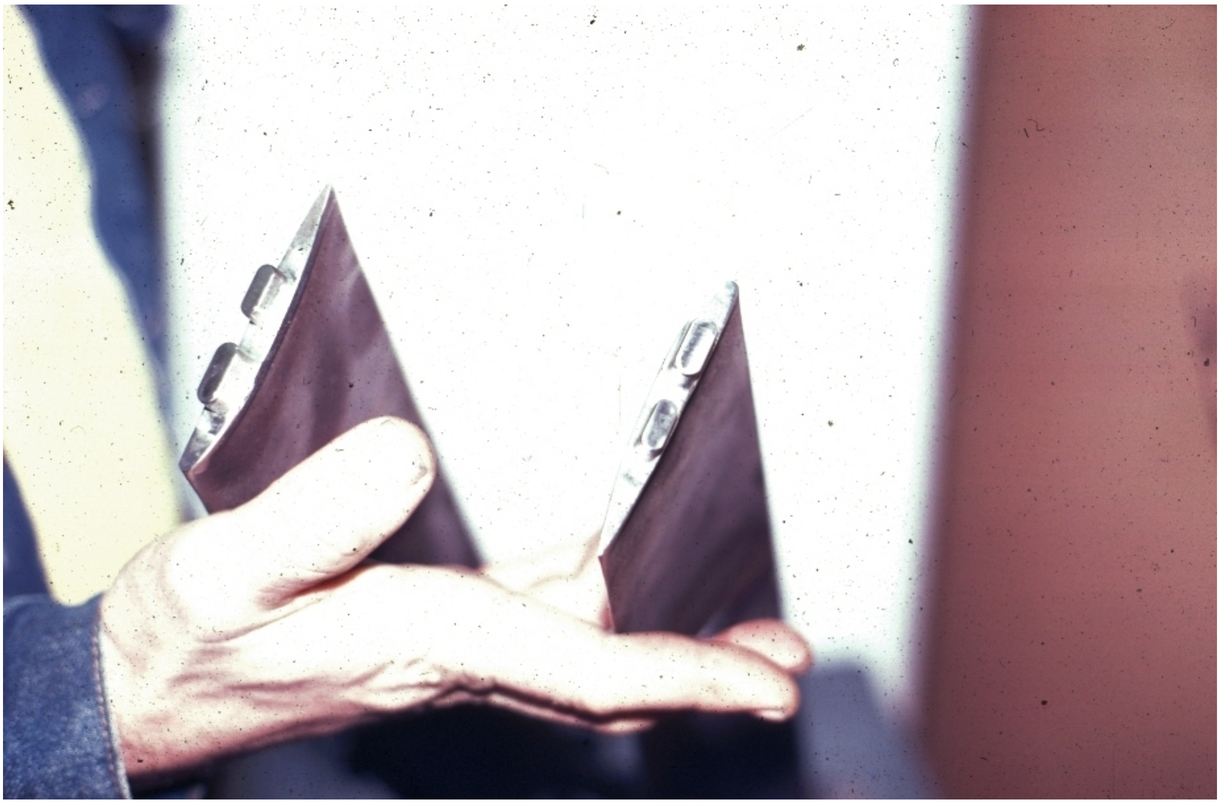
Unfortunately, after a little more than a year of operation, the repaired row failed again, this time breaking off two blades near the base of the foil. Again, cracks were found in the covers and when the covers were removed, tenon cracks were also found. Inasmuch as there were no spare blades available, the OEM (Original Equipment Manufacturer) recommended that the row be removed and a pressure plate installed. But because the manufacture and installation of the pressure plate required the 790 MW unit to be out of service for 12 weeks, this recommendation was unacceptable. Instead the owner/operator of the unit decided to repair the row by trimming off the original tenons and rebuilding the tenons with weld metal, stress relieving and reforming the tenons, installing new, full thickness covers, and shot peening the tenons and cover holes. It was also proposed to strengthen the design by underbrazing i.e. brazing under the cover at the interface between the blade tip and the cover), if this could be done without adversely affecting the tuning of the blades. Frequency checks were made on the assembled blading after tenon riveting, and verified after underbrazing that the tuning of each group of blading had not been adversely affected.

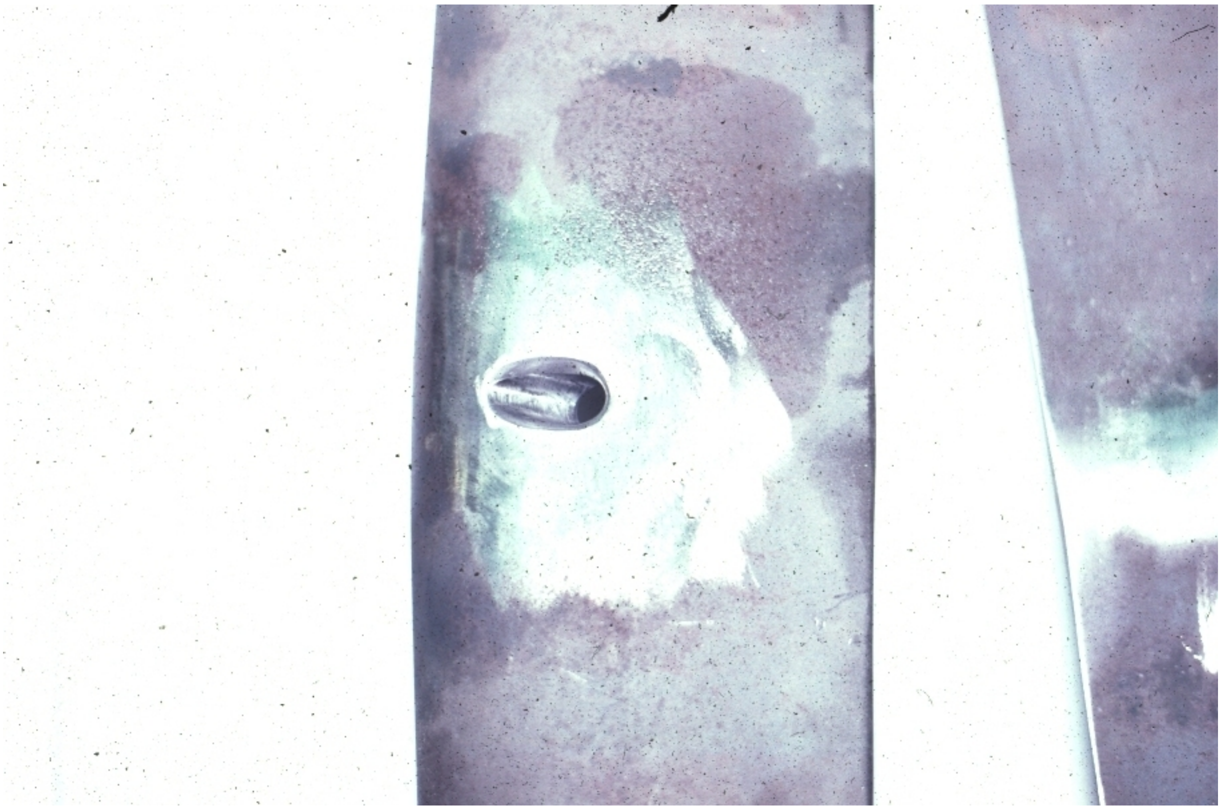
This repair was implemented in April 1975 and has been successful so far. The replacement row of blades which had already been purchased was retained as a spare row, and the repaired row left undisturbed. It has been examined several times since the repair and no defects have been found. (Improvement summarized- stronger, stiffer blade tips, lower stress on tenon, cover and blade, compressive surface stresses at base of tenons and in tenon holes due to shot peening, tuning verified and possession of spare blading.)

After more than 27 years of service, the two 790 MW supercritical units having L-2 stage rotor blading (two rows per unit) of the same design without a subsequent failure, other things become apparent with regard to the above experience. As the units aged, it became clear that there was a serious corrosion problem affecting virtually all supercritical LP steam turbines. In addition, the tuning of this particular L-2 stage design was dangerously close to the 3rd harmonic, and the stage which failed had a diaphragm which apparently produced a higher stimulus than the other three rows. The stiffening of the blade tips by brazing increased the frequency by 1 to 1 ½ Hz, helping to move its frequency further from resonance, reducing the vibratory stress. In the initial failure, the use of shotpeening was a sound idea, but the benefit was insufficient to make up for the loss of section modulus. In the second repair, the underbrazing is believed to have partially stress relieved the shot peening that was performed on the tenons and covers, but not enough to lose the compressive stress in the peened locations. This advantage will be explained later in the paper.

Since that first failure in 1973, the owner/operator has implemented underbrazing on 28 rows of blades without a single failure or discovery of cracking. Virtually all of these rows were underbrazed after the blading had been in service, and without cover removal and cleaning of the mating surfaces. This means that the increase in tip strength can only be based on the braze fillet, and no credit can be taken for braze bonding of the cover to the tip of the blade, as bonding will not occur on surfaces that cannot be cleaned. If sufficient improvement in tip strength cannot be achieved with underbrazing alone, then the procedure given above (i.e. remove covers and inspect all tenons, shot peen tenons and install new shot peened covers, clean all mating surfaces, and then underbraze) may provide the needed strength.

Other blading was found to be refurbishable (20.9" L-1 stage of 33.5 " end.), even though there was tie wire hole cracking and some pitting. The blade trailing edges were polished to remove pits, the tie wire holes with cracks were ground out and weld repaired. The tenons were rebuilt by welding, the tie wire holes were repaired by enlarging the hole edge radii, the pits were cleaned by chemical solution, and the tenons and tie wire holes were shot peened as indicated in the photographs that follow.





1181 MW SCC in Rotor Discs[4]
In two 1127 MW nuclear units, employing three LP rotors each, SCC was discovered after less than fifteen years of service, in the dovetails of the discs, entry slots and steam balance holes in several LP stages. Cracking prone dovetail fillets were skim cut and polished, extensive dress-out of defects was then effected and steam balance holes were enlarged in many areas. This was followed by shot peening.

In the second unit examined, titanium blades were selectively used to reduce centrifugal stresses in dressed out locations. Since the straddle root type blades were carefully removed to gain access to the disc rim, it was possible to reassemble these parts with minimal use of new parts. The rotors were reassembled in the unit and operated for more than 18 months at full load. During the subsequent refueling outage, the rows containing the deepest dress-outs were de-bladed and re-examined. No resumption of cracking was detected.

Repair Discussion
Approximately 300 excavations were performed on the stage 4 disc rims, the majority located on the bottom serration and almost uniformly distributed among the three LP turbines. The dimensions of each excavation were measured and recorded on a computer generated drawing in support of the engineering evaluation. Minor cracking was also discovered on the majority of the L-1 or stage 7-disc slot, side entry, firtree radii. This cracking was estimated as being less than .010" deep and was removed by hand dressing.

The last phase of the disc repair work prior to reblading was shot peening in order to produce a beneficial surface compressive stress at the highest stressed locations. The shot peening procedures were prepared by Metal Improvement Company working closely with the turbine OEM and utility's engineering and maintenance staff. An automatic process was developed for the fillets themselves and a manual process was used for the excavations, closing blade pin holes and steam balance holes. For the discs, the surface compressive stresses after shot peening were estimated at 80-90 ksi (56- 63 kg/mm²) with a penetration of .004 - .013 in. (.1-.3 mm).

Follow Up Inspection Results

The repair engineering evaluation specified a one fuel cycle of follow up inspections for verification of stage 4 repairs. The following results were obtained: One minor defect on LP1 rotor stage 4 rear dovetail, from MT inspection. Two minor defects on LP3 rotor stage 5 rear steam balance holes #s 5 & 6, from MT inspection. These minor defects were repaired by excavation of no significant depth. These results provided confirmation that, at least in the short term, SCC does not resume in excavated and shot peened locations. This confirmation prompted the utility to use the "skim and shot peen procedure" as a proactive measure for Units 2 & 3 HP turbine dovetail fillets. This effectively prolonged the life of the HP turbines and deferred or eliminated costly replacement of these components.

OTHER SHOT PEENING ACTIVITIES

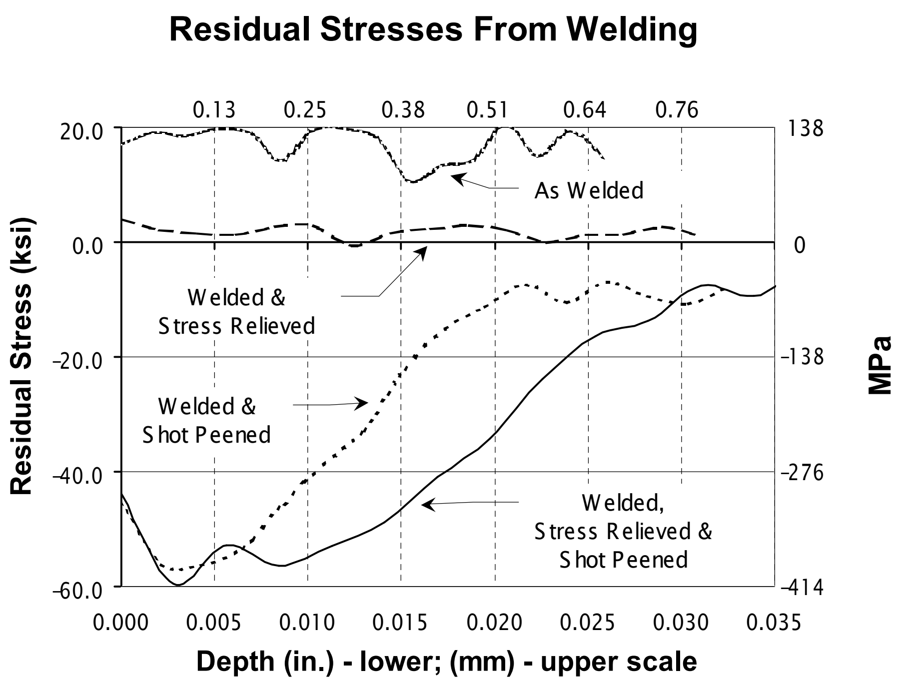
Shot Peened and Coated Blading

Shortly thereafter, this same electric power company began to examine the blading in their super-critical units and steps were taken to increase the fatigue strength of the blading in these units[5, 6, 7]. Where blading was refurbished and there was no pitting, the blades were cleaned, tenons restored by weld buildup, stress relieved, machined, polished, shot peened and given a corrosion resistant coating. In those cases where some minor pitting occurred, the pits were cleaned out by immersing the blades in a bath of potassium permanganate and then flushed with clean water. Shot peening followed and the coating used varied with the service intended.

In recent years, nickel-cadmium electroplate has been replaced by a zinc-nickel or nickel-zinc electroplate coating system. Where new blading is to be installed, if there was any history of cracking in the design, then shot peening would done to a prescribed procedure before coating. None of this blading has ever suffered subsequent failure due to steam induced fatigue or corrosion-fatigue stress. (One row of blades which had been repaired, shot peened and coated subsequently failed because of undetected water in the casing of an upward exhausting boiler feed-pump drive turbine in a super-critical unit, curling the shroud into a ball.) At the present time there are more than 200 rows of blades in service with one of the corrosion resistant coatings, and many of them have been shot peened. How long they will survive in a corrosive environment remains to be seen. Periodic examinations have shown that the best performing coating is nickel-cadmium (NiCd) electro-plate. However, it is believed that nickel-zinc electroplate or zinc-nickel electroplate will be superior to NiCd, because these coatings can be used in locations that will require subsequent heating for brazing or welding.

Using Shot Peening in Elevated Temperature Service

Most metal parts that have been machined, punched, stamped or fabricated by brazing or welding will possess residual tensile stresses. In the case of welded parts, heat stress relief only relieves 70% of the tensile stress remaining at the surface of the part. When a part is shot peened, the appearance of the dimples means that the surface of the part has been yielded at that location and since the yielded surface is a uniform deformation consisting of adjoining concave dents, the surface has been completely relieved of the residual tensile stress, and this stress has been replaced by a compressive stress. If the shot peened surface is then heated by nearby welding, brazing or service at an elevated temperature, the shot peened surface will become stress relieved. But as stated above, the stress relief will only remove about 70% of the stress. However, in this case, the remaining stress is a compressive stress. Thus, in the process of shot peening a stress relieved weld in a part which will operate in elevated temperature service (greater than 700° F, 371° C), the residual stress went from 30% of the yield tensile stress to 30% of the yield compressive stress, for an improvement of 60% of the yield in reduced stress.



USING SHOT PEENING FOR SURFACE ENHANCEMENT

Shot peening can also be used to improve the surface of the metal so that coatings which adhere to the surface mechanically will grip it better. Shot peening is routinely used to form aircraft wing skin and other curved surfaces, leaving a residual compressive stress on the convex surface, as well as a dimpled surface that could have less drag than an extremely smooth surface, much the same as a golf ball has a dimpled surface to reduce aerodynamic drag. The ability to produce a curvature in wing skin panels as if they were oversized Almen strips can be applied to other parts such as blade integral covers. Snugly assembled blading is a necessity and the blades can be made even snugger by shot peening the radially outer surfaces of the covers.

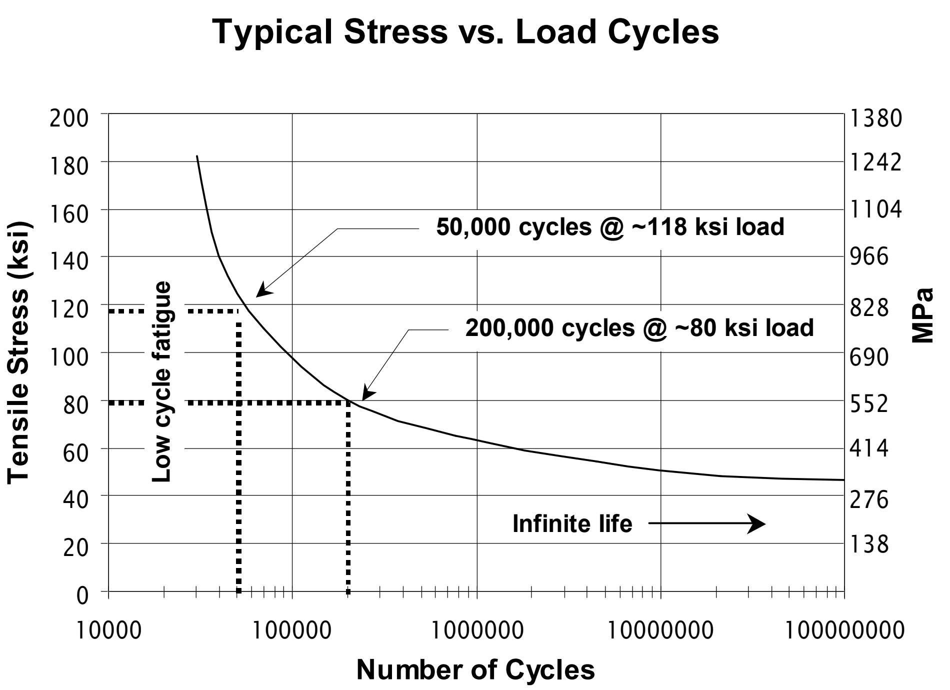
WHAT YOU SHOULD KNOW ABOUT SHOT PEENING [8]

Shot Peening Applications

There are two major applications of the shot peening process for Power Generation equipment. These are to improve fatigue life and minimize the incidence of stress corrosion cracking. While these two failure mechanisms are very different in the manner in which they occur, one major dynamic in both is the presence of tensile stress. These may be residual or applied stresses and both forms of stress may lead to failure of the part.

Fatigue Life Extension

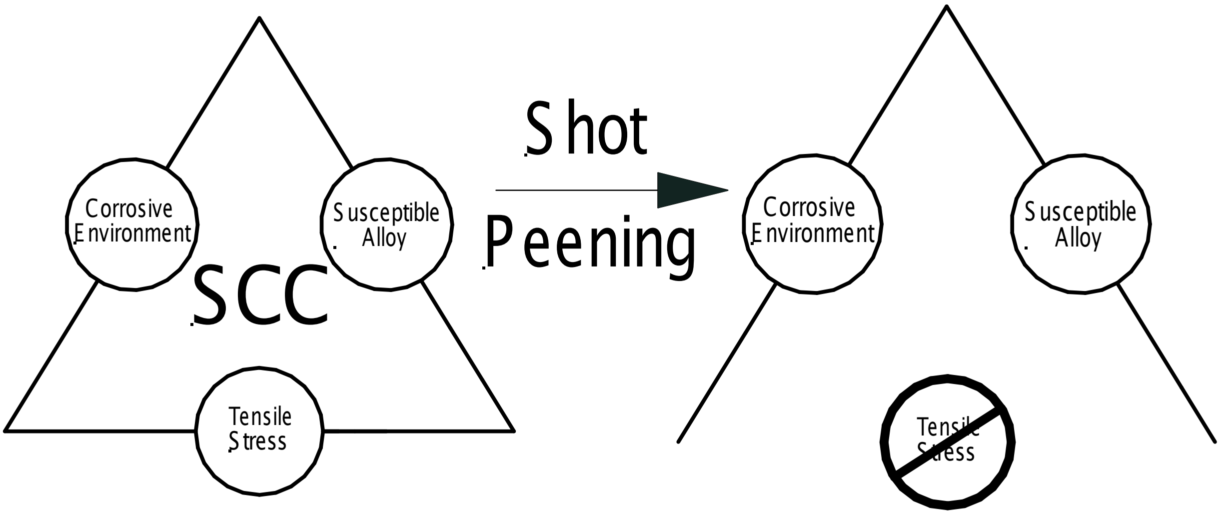
Shot peening provides benefits as it performs a surface stress conversion from tension to compression by cold work. This conversion to a residual compressive stress condition should be uniform and its magnitude is determined by material properties. This presence of residual compressive stresses will oppose crack propagation to improve fatigue life and eliminates one of the components required for stress corrosion cracking to occur.



Fretting Fatigue

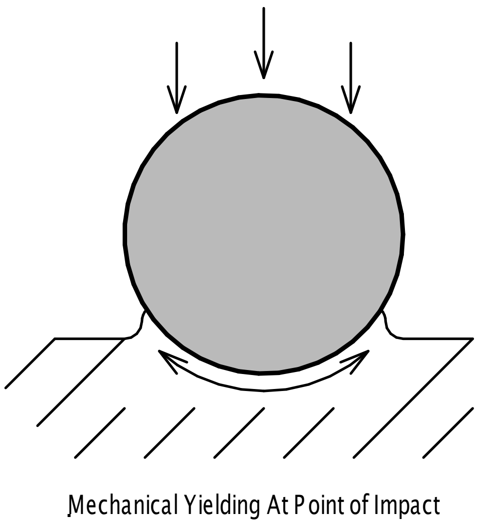
Specific case histories of fatigue life extension with rotor blades are detailed in other portions of this paper. Failures of rotor dovetails due to fretting fatigue have also been documented. The repair procedures for these failures include shot peening of both the turbine blade dovetails (root) and rotor dovetails.

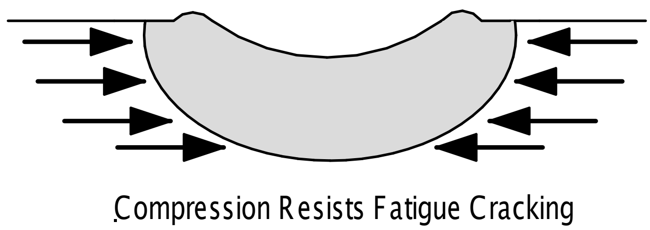
Stress Corrosion Cracking
Stress corrosion cracking (SCC) failure is most often associated with steady tensile stress. The steady stress may be applied at the time of part installation (fit-up stresses) or may be the result of manufacturing processes such as high speed machining, welding or cutting tool condition. Three factors influence the occurrence of SCC. These include:
1) Tensile stress (residual or applied)
2) Susceptible material
3. Corrosive environment



What Happens When a Part Is Shot Peened?

Shot Peening Mechanism
Shot peening is a cold working process in which the surface of the part is struck with small spherical media called shot. Each piece of shot striking the metal acts like a tiny peening hammer, imparting an indentation, or dimple on the part surface. To create a dimple, the surface layer of the metal must yield in tension. In addition, depending on the depth of the dimple, the surface will now have a compressive stress which can be as high as the yield stress of the material. Below the surface, the compressed grains try to restore the surface to its original shape, producing a hemisphere of cold-worked metal, highly stressed in compression.

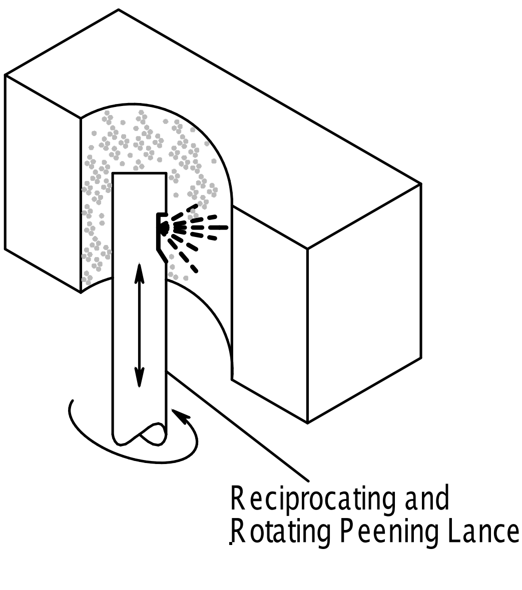


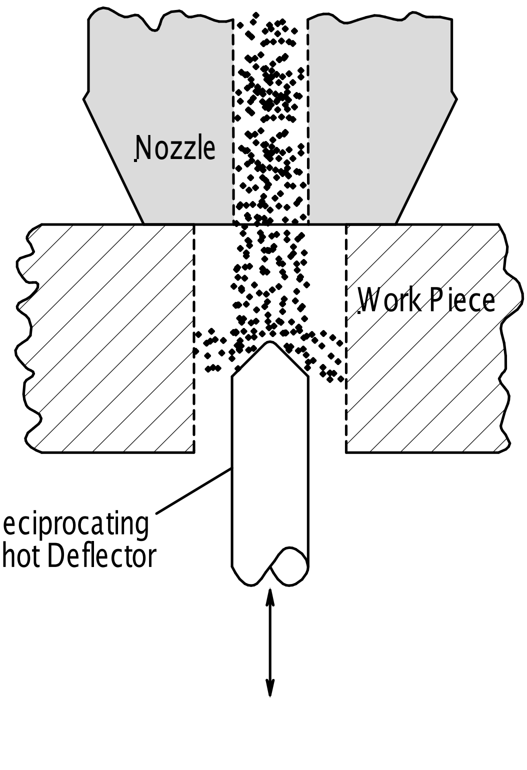


It is well known that cracks won't initiate or propagate in a compressively stressed zone. Since nearly all fatigue and stress corrosion failures initiate at or near the part surface, compressive stresses induced by shot peening provide significant increases in part life. The magnitude of residual compressive stress produced by shot peening is at least 50% of the yield strength of the material being peened.

For new parts, shot peening is usually done after final machining and heat treatment. It may also be done as a field process when parts have been in service. Automated equipment has been developed so that field applications can now provide the same levels of protection supplied to the OEM market.

Shot Peening of Internal Bores and Surfaces





When the depth of an internal bore is greater that its diameter, it cannot be effectively shot peened using external methods. An internal shot peening lance or internal shot deflector (ISD) method must be used under controlled conditions.

Holes as small as .096 (2.4 mm) have been peened on a production basis using the ISD method.

Potential applications for internal shot peening include:
1) Tie wire holes
2) Hydraulic cylinders
3) Shafts with lubrication holes
4) Turbine blade slots in discs and spindles

When Can Parts Be Shot Peened?

Parts can be shot peened when first manufactured or after they have been in service, or both. Sometimes parts in service are shot peened after it is discovered that they suffer from fatigue, corrosion fatigue or stress corrosion cracking. More than likely, they will not have previously been shot peened, and if the problem is discovered in time, it is possible to arrest it by appropriate action as described later in the paper.

What Preparations Are Required Before Shot Peening?

Part Preparation

Parts must be clean before they can be shot peened. For OEM applications, this requires that they be free of machining oils and other coatings. When performing this process in the field, parts must be clean and free of mineral build-ups that may occur in service. Parts must be accessible, which could involve moving them to access and/or processing areas where they can be tented or otherwise covered to contain media used in the shot peening process.

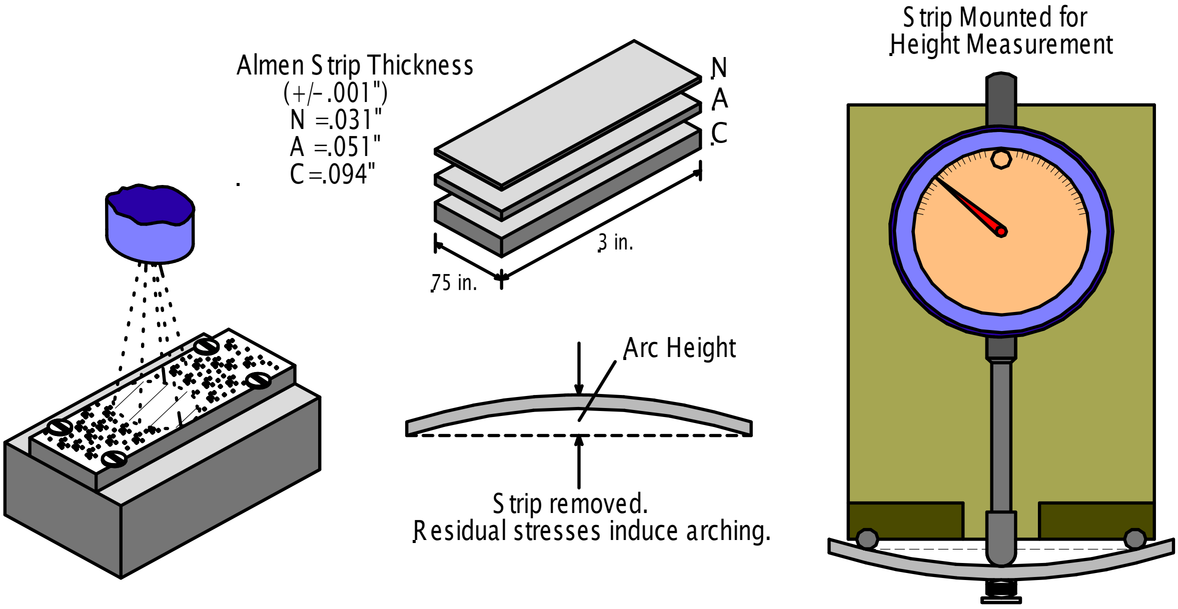
What Methods Are Used To Verify the Completeness of the Work?

Process Controls

There is no nondestructive method of confirming that the shot peening process has been performed to the proper specification. Techniques such as X-Ray Diffraction require that a part be sacrificed to generate full compressive depth profile analysis. To insure that applicable peening specifications have been met, the following process controls must be in place and followed:
1) Media quality and size
2) Intensity (kinetic energy)
3) Coverage
4) Proper class or type of equipment

Media
Peening media must be of uniform diameter. The impact energy imparted by the media is a function of its mass and velocity. Larger media has greater mass and potential impact energy. This could cause variations in impact energy that could result in inconsistent fatigue results. Broken or irregular shaped media may result in the creation of stress risers that could also affect fatigue results.

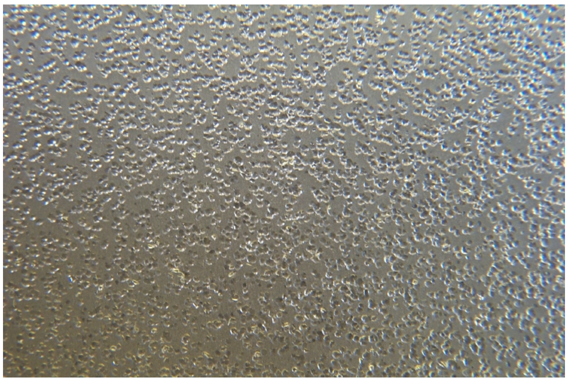
Intensity Control
Shot peening intensity is the measure of the energy transmitted by the shot stream. It is one of the essential portions of the process in ensuring process repeatability. Intensity is the measure of shot stream energy and is related to the depth of the compressive stress layer created by the peening process. Intensity is increased or decreased by changing the size of the media used, the velocity at which the media is delivered and the angle of impingement at which the media strikes the work piece. The greater the angle of incidence, the greater the amount of impact energy the media can impart to the work piece.



The measurement of intensity used in a shot peening application is done by use of test coupons called Almen Strips. Almen strips are made from SAE 1070 spring steel and are peened on one side only. The indentations or dimples made by the media striking the surface of the strip stretch the surface and cause it to curve. The strip is then placed on an Almen gage and the curvature measured and recorded. This curvature, called “Arc Height”, is a function of the energy of the shot stream and is very repeatable.

Coverage Control

Complete coverage of a shot peened surface is critical when performing high quality shot peening. Coverage is the measure of original surface area that has been obliterated by shot peening dimples. Coverage should never be less than 100%, as fatigue and SCC cracks can develop in the non-peened area that is not encased in residual compressive stress. In photos below, the left photo is significantly less than 100% coverage, while the photo on the right has a minimum coverage of 100%.



If coverage greater than 100% is called for (i.e. 150%, 200%), this means that the processing time to achieve 100% coverage is increased by that factor. The time to achieve 200% coverage would be twice the amount of time it takes to achieve 100% coverage.

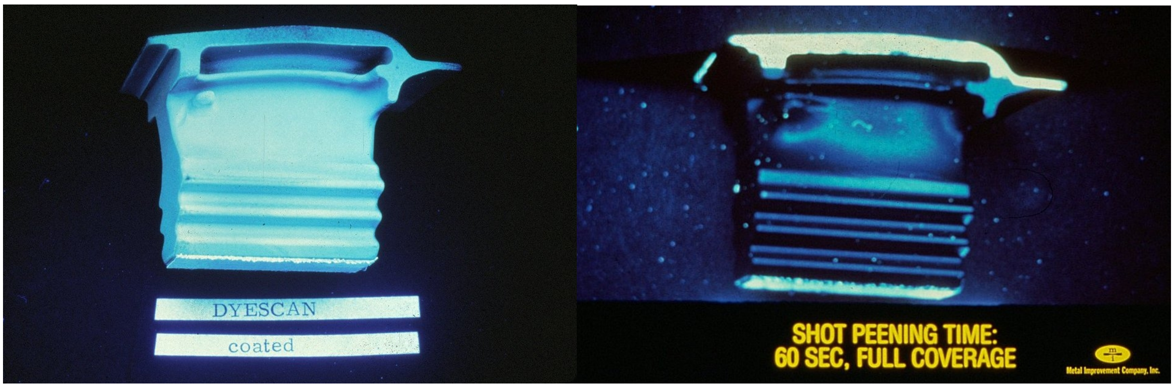
Peenscan for Coverage Control

Determination of 100% coverage for parts that are very small or which are made of softer materials can be fairly easy. When harder material is used, or when there are large part sizes or large quantities of parts, coverage inspection may be difficult. Internal bores, tight radii and parts with large surface areas also present a challenge when determining proper coverage.

A process utilizing a fluorescent tracer liquid has been developed that was so effective it was included in Mil S-13165, which was the military specification that governed shot peening. This process, called PEENSCAN®, utilizes a liquid that is UV sensitive and may be applied to parts using a brush, airless spray applicator or by dipping parts into the liquid. This material dries to an elastic condition and may be inspected by use of a black light. Under black light inspection, this material has a white glow, which allows you to determine that this liquid covers all areas of the part where 100% or greater coverage is required. The covered part is allowed to dry and may be shot peened within 20 minutes to 24 hours of Peenscan application.

The Peenscan-covered part is then subjected to the shot stream, where the media removes the Peenscan material. After shot peening, the part is inspected for coverage by using the black light again. If there are any areas where residual Peenscan material still exists, adjustments may be made to angles of impingement or run time to improve shot peen coverage of parts.

Peenscan has been proven superior to coverage inspection using a 10X or greater magnification loupe. It can also be a cost savings measure because of the speed with which coverage inspection can be completed.



Where specified, this inspection method can eliminate 10X manual coverage inspection of many parts.

What Non-destructive Monitoring Is Used in the Shot Peening Process?
Almen strips accompany all peening work, and constitute the primary non-destructive test. Peenscan is also used as a visual means for assuring completeness of the work.

Why Does Shot Peening Work in Avoiding Stress Problems?
Shot peening works because of the residual compressive stress left in the part after peening. In order for a crack to initiate, there must be tensile stress. Thus, the residual compressive stress must be unloaded before the surface can receive tensile stress. The net result is that loads which previously caused cracking become safe.

Is Field Application a Viable Alternative?
Field application has, by necessity, become an almost routine part of the work. Many parts are too large to transport to the peening facility. The co-author's company has become very proficient in performing complex peening operations in the field.

What Are the Pros and Cons of Insitu shot peening?
Insitu shot peening is often a necessity due to the size and weight of the component to be processed. Frequently, the pros and cons are whether shot peening will be performed, but the benefit to cost ratio is so high that the choice is virtually always to get the work done.

How Long Does Shot Peening Take?
Depending on the area to be peened, it can take minutes or hours. The benefits are so significant that the time and cost required are considered inexpensive insurance against failure.

How Much Does Shot Peening Cost?
The cost is so incidental in comparison to value of the parts that, as noted above, shot peening is often inexpensive insurance. But, because "time is money", sufficient time must be allocated to perform the shot peening process or it may not get done. In other words, the cost of down-time, in most cases, will be many times the cost of shot peening.

CONCLUSIONS

Shotpeening can provide a number of benefits to steam turbine steel components. The deformation of the metal surface not only assures that all tensile stresses have been relieved, but also that only compressive stresses are present. The result is that a significant improvement in fatigue resistance results, as well as a reduction in steady tensile stress at the surface of the metal when a load is applied. In addition, since cracking typically occurs due to steady tensile and/or alternating stress, the risk of several causes of cracking is reduced, such as: fatigue, corrosion fatigue, intergranular attack, stress corrosion cracking, and heat cracking. In older turbines the process is largely applied for enhanced life extension of aged or failed components. In new turbines the process is most often applied to increase design margins from failure and to partly compensate for largely unquantifiable long-term environmental effects which are out of the OEM's control.

The deformation of the metal surface by shot peening could have other benefits, traceable to the dimpled surface, such as reduced drag in compressible and non-compressible fluids, improved attachment of coatings, elimination of surface blemishes, increased surface hardness in hardenable metals thereby increasing wear resistance, and for forming thin sheets of metal by selective shot peening.

ACKNOWLEDGEMENTS

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