Very significant life extension of high speed turbomachinery parts subject to metal fatigue, corrosion fatigue and stress corrosion cracking can be achieved by the introduction of residual compressive stresses. Controlled Shot Peening will produce surface compressive stresses equal to approximately 60% of the yield strength. The process is used originally at manufacture and again at overhaul to restore levels of compression lost through service loads and vibrations, through fretting of mating surfaces and through corrosion or abrasion.

Controlled Shot Peening of blades and discs, particularly on roots and slots at periodic overhaul intervals, has long been employed in jet-engines. However, there are many opportunities to apply the technology to surface-based power generation or propulsion units and compressors.

A manufacturer of large steam turbines has both laboratory and field tested reshot peening of blades at 50% of their design life. Results show that life expectancy can be restored nearly as for new blades. The process is repeated at several more 50% life intervals before blades are finally retired. Other areas of frequent application on blades are tie-wire holes where fretting fatigue is evident or, similarly, on the weldments of mid-span lugs to reverse the high residual tensile stresses in the heat affected zone.

New computer controlled Shot Peening machines and practices are now in place that significantly increase the level of reliability and repeatability of Shot Peening for both in-house and field applications. The critical parameters of Shot Peening such as intensity, coverage, choice and condition of media are discussed, as they apply to turbomachinery maintenance.

Biographical Note:

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INTRODUCTION

Controlled shot peening is a process that involves the bombardment of metal parts by millions of tiny spherical particles. The purpose is to produce a thin surface layer of residually stressed material that will prevent or retard some of the more common mechanisms of metal failure.

Shot peening is used daily by the original manufacturers of Aircraft Jet Engines, and is a vital part of the overhaul and repair procedure of just about every rotating part (as well as many stationary ones) in the flying turbomachinery. Many compressor and turbine blades and discs will be shot peened six times before they are finally retired from service.

The life restoration properties of shot peening are just as applicable to land and marine based turbomachinery and are, in fact, used by some of the more astute users, at overhauls, to extend life of critical (and expensive!) components. However, because shot peening is applied only to critical parts, it is essential that the process be correctly specified. Also, because there exists no non-destructive method of determining that the part was shot peened correctly, controlling the process is of prime importance. It is for these reasons (as well as economy) that many original equipment manufacturers, users and repair stations prefer to employ the services of specialized shot peening companies for both "in house" or "on site" work.

THE APPLICATION

In rotating machinery, the more common mechanisms of component failure, apart from wear or erosion, are associated with high tensile stresses applied by centrifugal forces, by bending loads or by torsional loads. In many cases, these are aggravated by hostile environments leading to corrosion and/or abrasion. The tensile stresses are usually cyclic and highest at the surface of a component. Stresses are concentrated by the presence of notches, holes, thin sections, etc., resulting in premature failures from metal fatigue.

Fatigue in metals is a progressive failure: the very first tensile load cycle produces a sub-microscopic region of plastic deformation near the surface and each subsequent cycle increases this region until (hopefully many millions of cycles later) a crack initiates. The crack then grows progressively to the point where the remaining cross section of the part is no longer capable of sustaining the environment (clean water or steam, for instance) causes the crack to start sooner and to grow faster. The presence of abrasive particles causes sharp indentations in the metal where stresses are then concentrated, leading to the premature formation of cracks. Where there is a metal to metal fit-up, as in the blade root and corresponding disc slot of a turbine, high contact forces and low amplitude relative motion will cause fretting and the formation of score marks at the pressure faces, from which fatigue cracks can start. (Fig. 1, Ref.1)

![Figure 1: Rotating-Bending Fatigue Curve for 0.2C Steel](image-url)
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It is important that two points be clearly noted from the previous paragraph: 1) Fatigue failures are always progressive and 2) Fatigue cracks always initiate where tensile stresses are concentrated: never in areas that are in compression. In turbine, for instance, it is always the concave side of a blade that is in tension as the blade is bent backwards under load. Tensile stresses cause the material to stretch and crack; compressive stresses push the material together so that it will not crack.

From this, it follows that if compressive stresses can be introduced into the surface of a part and they will remain there under service loads, it should be possible to prevent or greatly retard the initiation of fatigue cracks. The most practical method to accomplish this is through the bombardment of the metal part by millions of tiny spherical particles: Shot peening. The impact of each particle produces a very small indentation or dimple. This creates a residual compressive stress in the surface material. The part is therefore pre-loaded in compression by shot peening and a service load must overcome the compressive pre-load before any crack can start. The result is that a shot peened part may outlive a non-peened part by a factor of ten. With the use of shot peening, parts can be designed so that they are lighter as well as stronger and the application in Jet Engines is obvious.

**FATIGUE LIFE RESTORATION**

All metal parts, whether shot peened or not, have a finite fatigue life if the service loads are high enough, which is generally the case in turbomachinery. Eventually, even a shot peened surface, under a high enough load and sufficient cycles, will lose the compressive stress and finally crack. However, shot peening at overhaul will restore the compressive stress layer to its original value (about 50% of the yield strength of the material) because shot peening yields the surface of the metal each time the part is repeened. Tests have shown that when parts are repeened before their fatigue life is used up (i.e., before a crack has started), then the fatigue life can be restored to what it was when the part was peened for the first time. It will actually have much greater fatigue life after being peened at overhaul. It is absolutely necessary, of course, that the parts be subjected to a dye penetrant, magnetic particle or similar inspection to determine that no service cracks are present before peening. (Fig. 2, Ref. 2)

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**FIG. 2 SUPPRESSION OF FATIGUE DAMAGE OF INCONEL 713C TURBINE BLADES BY SHOT PEENING.**

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**THE SHOT PEENING PROCESS**

Shot peening, or "impact prestressing" as it is becoming increasingly known for the prevention of metal failures, requires that thought be given to each of the following items:

- What is the anticipated or historical mode of failure? Examples are fatigue (bending, axial, torsional: high or low cycle) stress corrosion cracking, corrosion fatigue, contact fatigue, fretting, galling, etc.
- What is the material of the part to be peened? It is steel (normal, high strength or stainless), titanium, aluminum, heat resistant alloys, others? Will it work harden?
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- What is the condition of the surface? It is as cast or forged, rough machined, smooth ground, polished, EDM'd, chem-milled? (Refs. 3,4,5)
- Are the stresses only applied in service or are there residual stresses present from grinding, quenching, welding, plating, forming?
- Does the part geometry and/or coating create stress concentrations? Are there fillets, holes, changes in cross section, machined or brittle surfaces?
- What is the service environment? It is neutral, corrosive, abrasive, high or low temperature?
- Does the part have very thin sections or small holes that require peening?

Shot peening parameters will be based upon these considerations. While space will not allow each of them to be addressed in detail, those that have particular application to turbomachinery

Impact prestressing, as the new name implies, produces in the surface of a treated part a very high residual compressive stress, approximately equal to 50% of the yield strength. (Fig.3 & 4) Since most forms of catastrophic metal failures start with surface tensile stresses, either applied or residual (though in most cases it is a combination of both), preloading the surface in compression (see Fig. 3 & 4) will prevent or retard the failure initiation and/or propagation.

For the prestressing to be effective, the layer of compressive surface stress must be deep enough to extend below any surface discontinuities, such as machine marks. To generate the maximum residual compressive stress, a metal must be peened with a media that is at least as hard as that metal. High strength steel parts should be peened with hard shot (55-62HRC). If the metal is non-ferrous, an inert media such as glass, ceramic, or stainless steel shot is preferred to preclude the subsequent necessity of decontamination and/or passivation.

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**FIG. 3 WHY SHOT PEENING WORKS.**

1. Impact of a high speed pellet creates a dimple of diameter "D". The depression is about 1/10 D.
2. The surface is stretched by the impact. The depth of the stretching is approximately "D".
3. The "not stretched" core exerts a compressive force in attempting to restore the surface to its original condition.

**FIG. 4 STRESS DISTRIBUTION IN A METAL BAR.**

1. Bar under applied load, showing dangerous tensile stress on upper surface.
2. Bar after shot peening. High residual compressive stress is shown on upper and lower surfaces.
3. Shot peened bar under same applied load exhibits resultant stress which is the summation of the residual compression and the applied tension. Note that now the stress on the upper surface remains safely in the compressive zone, even though a high tensile stress has been applied.
Part geometry must be considered carefully. Tight fillets must be peened with shot no larger than half the fillet radius. (Ref.6) Thin sections require light peening intensity and careful treatment, or deleterious core stresses or distortion will be the result. Small through holes, down to about .080 in. can be peened successfully but the cost is relatively high compared to wide open areas. Environment may dictate a heavy layer of compression if the part is subject to abrasion from airborne debris or to general corrosion.

The depth of the compressed layer is a function of substrate hardness and the kinetic energy delivered by the shot. A very elegant and simple system of coupons was developed by J.O. Almen that combines the elements of the kinetic energy that is imparted to the substrate: Shot size (mass), velocity and angle of impingement. (Figs. 5 & 6) The coupons are measured after peening and the number can be related to the depth of compression in a material of known hardness. Repeatability of the compressed layer is thus assured. It is absolutely essential that all the surface of the critical areas of the part be impacted by the action of the shot. On soft materials this can be determined visually under 10X magnification but on hard materials or areas of difficult visual access, the use of specially formulated fluorescent tracer lacquers is highly recommended. (Ref.7) 100% coverage is particularly critical in tensile stress corrosion cracking situations. Coverage, of course, is a function of part exposure to the shot stream and it follows that only automated machines make possible the highest repeatability of this parameter.

The condition of the shot itself is an important parameter that also must be monitored. Broken, angular shot can produce the negative effect of introducing stress risers rather than suppressing them. Good shot peening practice calls for machines that separate the shot according to size and also eliminate the non-round particles from the peening media. (Ref.6)
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Fig. 6 THE SHOT STREAM LEAVES RESIDUAL STRESSES THAT MAKE THE ALMEN TEST STRIP ARC UPWARDS. THE ARC HEIGHT SHOWS PEENING INTENSITY.

COMPUTER CONTROLLED IMPACT PRESTRESSING

An inherent difficulty in shot peening is that the critical parameters outlined above cannot be discerned on a part after it has been shot peened. Simply put, there is no non-destructive method of measuring shot peening on a part. Many parts are being processed now by computer controlled shot peening and hard data is produced for individual parts to show that each has been processed to the correct parameters. Experience has shown that the higher cost of the computerized equipment is essentially offset by significantly less post-peening inspection time.

The computer controlled shot peening machines are equipped to continuously monitor the parameters listed below:

A) Shot flow for each nozzle/wheel.
B) Air pressure and air flow for each nozzle.
C) Rotation speed for each peening wheel.
D) Speed and position of translation of nozzle(s)/wheel(s) in each axis motion.
E) Sequential operation of nozzle(s)/wheel(s).
F) Speed and position of part rotation and translation, in each axis of motion.

Items D, E, and F are controlled by the computer, which also has the ability to record, in hard copy form, the above parameters for each part in each lot that is shot peened. The computer is programmed to interrupt the processing cycle automatically, within seconds when any of the established limits are exceeded. If the cycle is aborted, the computer will retain in memory and can print out the abort details. It is also capable of resuming operations to complete the balance of the process cycle, when the out-of-limit condition has been corrected.

While many components of turbomachinery can be dismantled in overhaul and sent to a shot peening contractor for processing, there are many parts too large to move, steam turbine rotors being a good example. Under these circumstances, semi-portable equipment and field crews are available for deployment to any part of the world.

CONCLUSION

Controlled shot peening is a very effective and well proven method of enhancing and restoring fatigue life to turbomachinery components. The process requires stringent controls for it to be relied upon but it represents a very technically and economically sound method of returning undamaged components to service when most of their initial potential fatigue life has been used up. The cost of re-shot peening is a small fraction of that of a new component.
REFERENCES


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