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A METHOD OF AVOIDING CATASTROPHIC FAILURES IN TURBO-MACHINERY

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ABSTRACT

Catastrophic failures in turbo machinery are most often attributed to metal fatigue, a phenomenon that is the result of cyclic tensile stresses acting upon the doomed part. Turbine components are subject to tensile stresses from axial centrifugal force, from bending and from torsion. In many cases, as in blades, all three may be present and the detrimental effect is further aggravated by environmental conditions (corrosion fatigue); by localized wear (fretting fatigue); by rolling or sliding pressures (contact fatigue) and by some manufacturing processes such as welding or grinding. Tensile stresses are usually highest at the surface and are concentrated by notches, holes, heat affected zones and physical damage.

All metal fatigue failures are progressive and always start in areas of greatest tensile stress concentrations: never in an area where the stress is compressive. Given that axiom, introduction of high magnitude, residual compressive stresses into the surface of the turbine parts before service, makes good sense from a stress analysis standpoint. This can best be accomplished by subjecting the parts to controlled shot peening. The process will eliminate any residual tensile surface stresses that may be present (from grinding, for instance) and induce in the surface beneficial compressive stresses equal to at least 50% of the ultimate strength of the material.

Jet engine designers, faced with the added problem of reducing weight, use shot peening extensively, but there are still many opportunities to apply the process to non-flying rotating machinery. Some steam and gas turbine manufactures actually have their blades and disks re-peened at each overhaul interval to restore the fatigue life to the original (as manufactured) level. The economics of this practice far outweigh the modest cost of the rejuvenation shot peening involved.

INTRODUCTION

Turbo machinery, by the fact of its high speed of rotation usually in less than ideal environments, becomes subject to almost the entire gamut of known modes of metal failure. Catastrophic failures are most often associated with high tensile stresses applied by centrifugal forces, by bending loads or by torsional twisting. Hostile environments introduce the further life shortening factors of heat, corrosion and/or abrasion. The applied tensile stresses are usually cyclic in nature and highest at the surface of the components and are concentrated by the presence of notches, holes, thin sections, etc. Turbine and compressor blades, under severe operating conditions (in jet engines, for instance) actually can experience all of these hazards. Designers, therefore, seek not only the best material but also try to give that material as much protection as possible through control of surface stresses and through coatings.

HOW FAILURES HAPPEN

Metal fatigue is always the result of cyclic tensile stresses acting upon a part and most often starts as a minute crack originating at an area of tensile stress concentration at the surface. Design of turbo machinery components is usually a compromise between functional requirements and reducing stress concentrations. Reducing mass is also an all-important consideration but it acts inversely to increase applied stresses and stress concentrations when thinner sections are chosen. Unfortunately, when the designer is finished, he has little or no control over the manufacture of the part, which can actually have a very negative effect on the life of that part. Broaching lines in the fir-tree sections or gear tooth roots are sites of potential fatigue crack initiation. Sharp corners, both inside or outside, have similar effects. Grinding of blade profiles introduces residual tensile stresses into the surface that can equal the yield strength of the material, reducing fatigue strength dramatically and making the part highly susceptible to stress corrosion cracking. Welding of tie wires or mid-span supports creates a number of detrimental effects all in the heat affected zone: extreme residual tensile stresses; brittle untempered metal immediately adjacent to an annealed zone; porosity; a mechanical stress riser - all of which, untreated, contribute to reduce fatigue and stress corrosion resistance to half or less. Electro discharge machining (EDM) can be thought of as the reverse of welding, where molten metal is removed rather than deposited, but the negative effects at the surface are very similar. A further danger with EDM results from spark burns which produce spots of very brittle untempered martensite. Even many coatings, designed to retard wear and/or corrosion, can have a debiting effect on fatigue strength: they can be brittle and themselves cause residual tensile stresses in the surface, both problems contributing to early fatigue failures (REF. 1).

Tensile stresses under dynamic loading cause the surface to pull apart into fatigue cracks, whether the tensile stresses are residual or applied. Also, tensile stresses are the prime component of stress corrosion cracking: the other components are a susceptible material, an aggressive environment and time. (Fig. 1) If the stresses are cyclic, the failures are called corrosion fatigue. When in addition a low amplitude friction occurs (as in the contact surfaces of dovetail slots or tie-rod holes in discs) fretting fatigue may result from the stress concentrations developed by the friction. (Fig. 2)

BENEFICIAL STRESSES

If tensile stresses pull the surface apart, compressive stresses can be thought of as causing the surface to push together. This is best illustrated by a bar of metal under a bending load (Fig. 3 & 4). One side is stretched in tension while the other is squeezed under compression. Any cracking would naturally occur in the tension side. It follows that if compressive stresses can be generated on both sides of the bar, then the bar can be given a great amount of protection from fatigue and environmentally assisted cracking. Just as some processes generate detrimental residual tensile stresses of high magnitude, there are others that can generate compression.

Surface heat treating processes (good examples are carburizing and induction hardening) are effective in introducing residual surface compressive stresses and are often used on gears and shafts but not all metals can be heat treated in this way. Rolling of the surface, using special tools, also produces compressive stress but rolling is geometry dependent, usually limited to fillets of cylindrical parts. Shot peening, where a part is bombarded by millions of tiny spheres of steel, glass or ceramic, has a similar surface displacement effect as in rolling but it is effective on practically any metal and any geometry. In fact, many very hard carburized or induction hardened parts are shot peened to further increase the residual compression. Shot peening is so versatile that it has been used effectively on 80 ft (25 m) steel columns of a 55,000 ton forging press and on tiny springs of 0.010 inch (0.25mm) wire for television tuners.

In turbo machinery, the most examples come from the aircraft jet engines where a combination of light weight, high stresses, aggressive environment and prolonged service life demands the utmost from materials and designs. Shot peening is used on practically every rotating compressor part, as well as many of the stationary components. In the hot turbine section, many parts are also peened since the materials used are capable of retaining the compressive stresses at high temperatures. Even parts designed for temperatures that exceed the stress relief level are often peened to negate surface residual tensile stresses that can cause thermal micro-cracks during the first heat cycle, particularly in areas of weld repairs. (Fig. 5 Ref. 3) Shot Peening is also used very effectively on surfaces that have been EDM'd and on surfaces that will be subjected to thermal metal sprays or other forms of coating, including electroplating (Ref.4)

Stationary gas turbines and turbo compressors have some advantages over aircraft engines in that they operate under less stringent service conditions. Because they run at a constant speed, harmonic vibrations can be tuned out, for instance, and weight of the components in not such a critical consideration. Nevertheless, the service life of many parts, notably blades and discs, is improved significantly by shot peening for many of the same reasons cited above. Steam turbines are in the same category with the additional hazard of water drop erosion, which can be attenuated by increased surface hardness of the blade material. The austenitic stainless steels of which the large steam turbine blades are made, work harden well under cold impacts and shot peening is the ideal process to supply this energy. At the same time, the residual compressive stresses, induced by the shot peening, lessen the danger of fatigue cracks initiating at water drop eroded sites. If the design includes an erosion shield strip, shot peening can be used to improve the fatigue resistance of the zone affected by the heat of brazing or welding. (Fig. 6)

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 because shot peening yields the surface of the metal each time the part is repeened. Test 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 is was when the part was peened for the first time. If the part was not peened during original manufacturing, then 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. 7)

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:

- o 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.
- o 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?
- o What is the condition of the surface? It is as cast or forged, rough machined, smooth ground, polished, EDM`D, chem-milled? (Refs. 6,7, & 8)
- o Are the stresses only applied in service or are there residual stresses present from grinding, quenching, welding, plating, forming?
- o Does the part geometry and/or coating create stress concentrations? Are there fillets, holes, changes in cross section, machined or brittle surfaces?
- o What is the service environment? It is neutral, corrosive, abrasive, high or low temperature?
- o 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 are discussed below.

Impact prestressing, as the name implies, produces in the surface of a treated part a very high residual compressive stress, at least equal to the yield strength. 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 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.

Part geometry must be considered carefully. Tight fillets must be peened with shot no larger than half the fillet radius. (Ref. 9) 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 sucessfully 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 material 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 transfered to the part: shot size (mass), velocity and angle of impingement. (Figs. 8 & 9) The coupons or Almen strips are measured after peening and the amount of curvature 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 florescence tracer lacquers is highly recommended (Ref. 9 & 10) 100% coverage is particularily 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 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. 10)

COMPUTER CONTROLLED IMPACT PRESTRESSING

An inherent difficulity 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 parametes. 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 continously monitor or determine 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 interupt the processing cycle automatically, within seconds, when any of the established limits are exceeded. If the cycle is aborted, the computer willretain 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. (Ref. 11)

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.

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NOTE: FIGURES WILL BE INCORPORATED IN BODY OF TEXT ON FINAL COPY.

FIGURE 1.

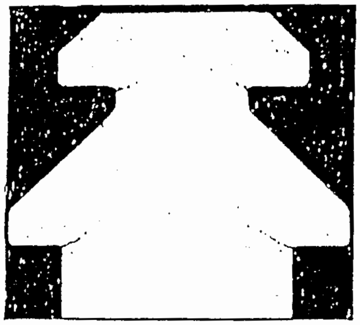


FIG. 1 TYPICAL SCC FAILURE
OF STEAM TURBINE WHEEL (REF 1)

FIGURE 2.

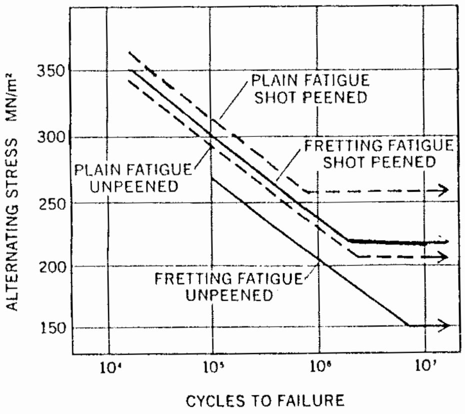


FIG. 2 ROTATING-BENDING FATIGUE
CURVE FOR 0.2C STEEL. (REF.2)

FIGURE 3.

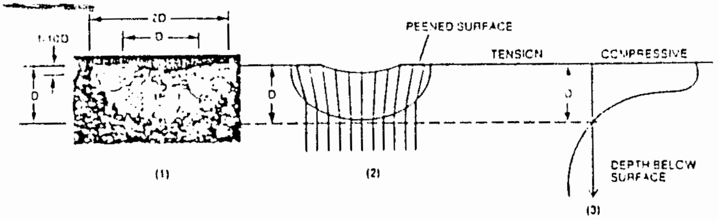


FIG.3 WHY SHOT PEENING
WORKS.

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.

FIGURE 4.

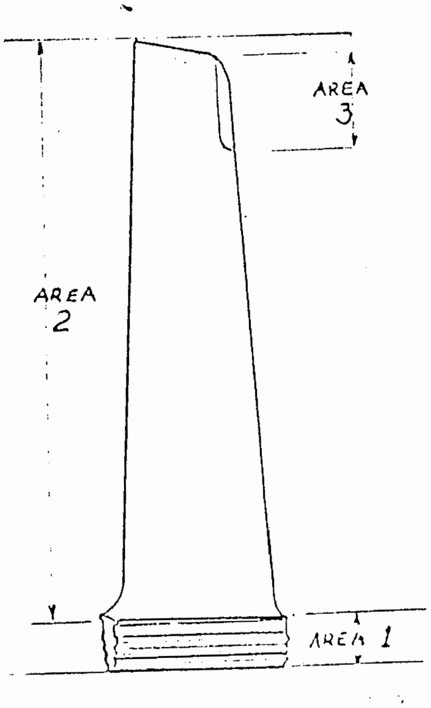


FIG. 6 LP STEAM TURBINE BLADE SHOT-PEENED ALL OVER. THREE DIFFERENT SHOT PEENING CALL-OUTS DICTATED BY DIFFERENT SERVICE CONDITIONS (REF. 5)

FIGURE 5.

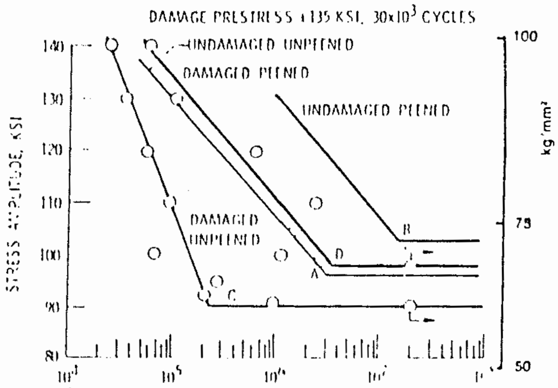
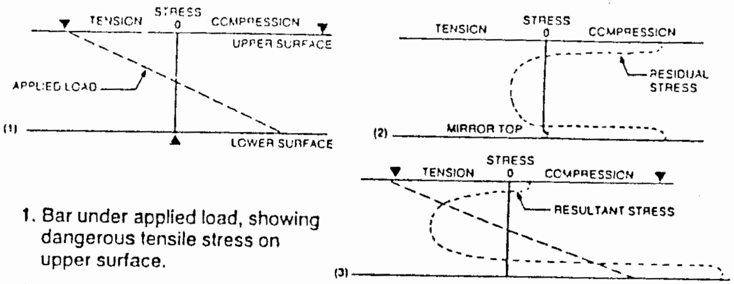


FIG. 7 - SHOT PEENING AS A MEANS OF OVERCOMING PRIOR FATIGUE DAMAGE WITH 4340 STEEL TESTED IN ROTATING BENDING. (Ref. 3)

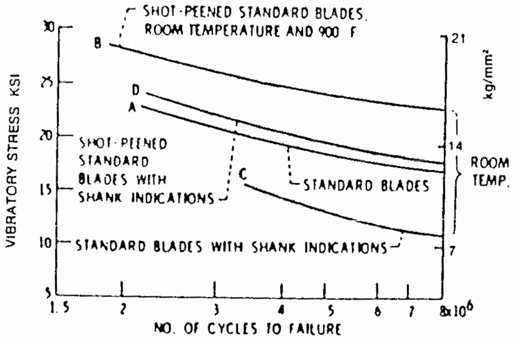
FIGURE 6.

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 through a hioh tensile stress has been applied.

FIGURE 7.



RETYPE

FIG.5 SUPPRESSION OF FATIGUE
DAMAGE OF INCONEL ~~713C~~ 718C 3
TURBINE BLADES BY SHOT
PEENING. (REF. 2)

FIGURE 8.

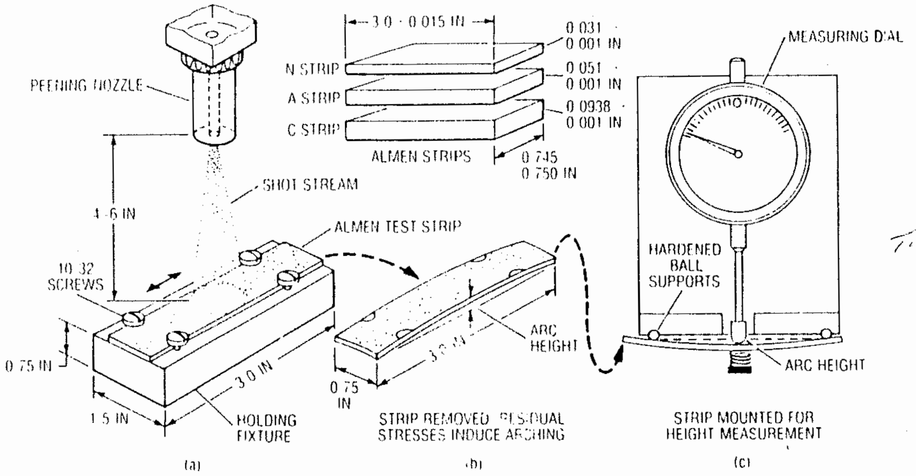


Fig. 8 THE SHOT STREAM LEAVES RESIDUAL STRESSES THAT MAKE THE ALMEN TEST STRIP ARCH UPWARDS. THE ARC HEIGHT SHOWS PEENING INTENSITY.

FIGURE 9.

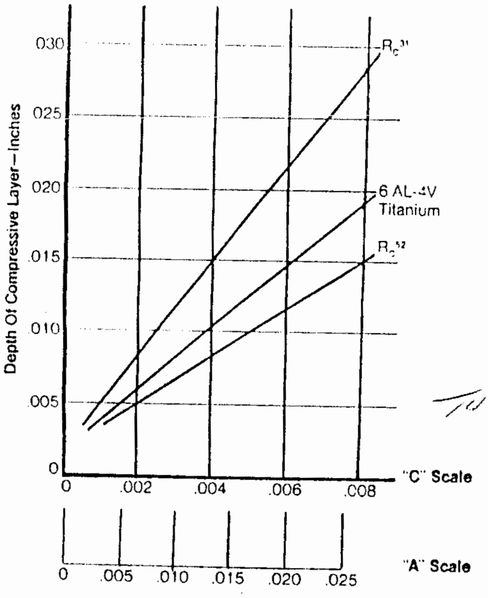


FIG 9 THE HARDER THE MATERIAL BEING PEENED, THE SHALLOWER THE DEPTH OF THE COMPRESSIVE STRESS LAYER RESULTING FROM PEENING AT A PARTICULAR INTENSITY (ARC HEIGHT).