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Shot Peening Plays a Vital Roll in Rejuvenation of Aging Aircraft

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ABSTRACT

Aircraft Components design engineers are very well aware of the benefits of surface residual compressive stresses on new parts as a means of retarding or even preventing catastrophic failures from fatigue, fretting fatigue, corrosion fatigue and stress corrosion cracking. Each of these failure modes depends on the presence of surface tensile stresses either residual or applied but, in service, usually both. It has been common practice, on parts for jet engines, propellers and landing gear, to reintroduce surface compressive stresses at overhaul intervals. Thousands of such parts are shot peened every day for rejuvenation purposes. Airframe parts present a different problem since they are not normally dismantled at overhaul and it is precisely these parts that come to mind when we consider "aging aircraft". Airframe components, whether they are steel, aluminum or titanium, can be rejuvenated by the introduction or restoration of surface residual compressive stresses, in most cases without requiring dismantling from the aircraft. This paper also reviews practical methods of shot peening aircraft structures "in situ", using inert media, under fully controlled conditions of Almen intensity, coverage, angle of impingement, media recovery, etc. Examples of actual applications on commercial and military aircraft are covered in detail, including offsetting the debiting effects of exfoliation corrosion. Peen forming of wing skins on aircraft is also addresses.

Keywords: Metal failures, fatigue, fretting fatigue, corrosion fatigue, stress corrosion cracking, exfoliation, aging aircraft, shot peening, peen forming.

INTRODUCTION

General corrosion and metal fatigue of aging aircraft structures is easily visualized by the flying public and dramatized by the media. Dramatics aside, the incidence of structural or skin failures have been so few as to be, statistically at least, almost nonexistent when considered in the context that there are about 3,500 aircraft just in the U. S. airline fleet, accounting for 17,000 flights each day and half a billion passengers per year. Approximately 18 percent of these aircraft are older than 20 years. Ultimately, the safety of the older aircraft depends on the quality of the maintenance performed. On March 6, 1990 the Federal Aviation Authority (FAA) adopted new regulations regarding extensive structural modifications to older aircraft[1]. These regulations apply to the large commercial airlines with which we are all familiar. However, of the 3,500 aircraft mentioned above, about 1,800 are the so-called "commuters", by definition carrying less than 60 passengers and operating in domestic, regional service. This fleet is made up of 59 different types of airplanes from 17 (mostly foreign) manufactures, and operated by no less than 165 different carriers. The Small Airline Directorate of the FAA has the responsibility for the Aging Commuter Aircraft Program[2]. The above facts are presented only to give some perspective to engineers not associated with the aircraft and airline industries. There are also large numbers of military and private aircraft that are not counted here.

STRESS CORROSION CRACKING AND CORROSION FATIGUE

While not wishing to minimize the problems of general and pitting corrosion which are universally well understood, amongst corrosion engineers within the aircraft industry there is an awareness that catastrophic failures are more often the result of environmental attack aggravated by the presence of tensile stresses. By definition, "stress corrosion cracking" (SCC) is the result of corrosion plus static tensile service stresses while "corrosion fatigue" (CF) is the result of corrosive attack plus dynamic tensile service stresses, often combined with, in either case, residual tensile stresses still present in the material from manufacturing operations such as forming, machining and grinding[3] (Figure 1). Both failure mechanisms require very little corrosive action to cause cracking when there are tensile stresses present at a value above the threshold level for the material. To make the situation worse, corrosion is visible -- tensile stress is not.

General and pitting corrosion normally take place over an extended period of time with a good possibility that they can be visually identified well before total failure occurs. Not so with SCC and CF: these failures can happen very rapidly once corrosion has penetrated the barrier coating on susceptible materials. The high strength aluminum alloys, particularly 7075-T6 and 7079-T6, that were used during the '60s and '70s for aircraft construction, were susceptible to environmentally assisted stress cracking particularly in exposed end grain areas[4] (Figure 2). Since SCC and CF may occur in the presence of surface tensile stresses even in just a mildly saline atmosphere, most of the aluminum structural components were shot peened after final machining and prior to anodizing[5] (Figure 3).

SHOT PEENING FOR FAILURE PREVENTION

During controlled shot peening, parts are bombarded by millions of tiny (typically, 0.75mm or 0.030 inch diameter) spherical particles of steel, glass or ceramic. The impact of each round particle indents the surface and the unyielded, subsurface material exerts a force that tries to restore the surface to its original condition. This action introduces a layer of residual compressive stress of a magnitude that at least equals 50% of the ultimate tensile strength of the material. The depth of the compressive layer extends, for aluminum, to a depth of about 0.5mm (0.020 inch)[6] (Figure 4).

As long as the surface remains under compressive stress, it is protected against SCC and CF (and ordinary metal fatigue, for that matter) because, as previously mentioned, these failure modes depend on the presence of tensile stress, as documented by Zoeller and Cohen[7], Lifka and Sprowls,[8] and many others. A very comprehensive work was issued by the Metals and Ceramics Information Center, under the title of "Shot Peening for Improved Fatigue Properties and Stress-Corrosion Resistance" J. E. Campbell of Battelle, Columbus[9]. There are three principal factors, though, that can, over time, remove the compressive stresses. One is heat that will stress relieve the component but heat is not usually a problem in aircraft structures. Another is service stresses that eventually will yield out the compressive stresses at the surface. The third is the physical removal of the surface layers, by general or pitting corrosion or exfoliation (and any machining to remove the corrosion) which, in addition, introduces stress concentrations and reduces the effective cross section and load carrying capacity. In all these cases, the compressive layer can be restored by repeating the action of the controlled shot peening process.

When aircraft parts are shot peened during original manufacturing, the applicable specifications almost unanimously demand automated or even computer controlled and monitored peening machines[10 & 11]. The use of hand held nozzles or flapper wheels is not permitted either by specific instruction or default. There are excellent reasons for this position. For maximum effectiveness, shot peening must produce:

1) A layer of compressive stress at an even depth, achieved by ensuring that the energy transferred to the part ie., the Almen intensity,[12] (Figure 5) is uniform throughout the surface. The transfer of energy, in addition to the shot mass and velocity, is very dependent on the angle of impingement and the distance between the nozzle and the work piece; parameters difficult to control on hand operated equipment. The Almen intensity is particularly critical on thin sections and must be a careful balance between achieving sufficient depth of compression to get below any surface discontinuity, such as

machine marks, corrosion pits or incipient micro-cracks, and the avoidance of distortion of the thin sections.

2) 100% coverage which, if anything, is even more critical than intensity and is defined as the total obliteration of the original surface by the dimples produced by peening. This is difficult enough to determine using the standard 10X magnifier on a newly machined surface but is virtually impossible on a surface that has been peened previously. The use of a fluorescent tracer liquid[13] (Figure 6) is recommended but must be used with some judgement, especially on aluminum.

The impact of a single piece of shot creates a visible dimple surrounded by a subsurface hemisphere of cold worked metal stressed in compression which in turn is surrounded by an area of tension[14] (Figure 7). If coverage is not complete, shot peening can actually create tensile stresses at the surface; a very undesirable situation in a corrosive environment. It requires a great deal of experience to ensure complete coverage of large and/or complex areas with manual peening but it is virtually impossible with flapper wheels. Exhaustive testing by a leading builder of nuclear generating equipment caused them to defer their preferred convenience of flapper peening in favor of the much more reliable, computer controlled shot peening to prevent SCC inside thousands of Inconel 600 tubes in 20m (60 feet) high steam generators[15] (Figure 8). Flapper wheels are also of little value in tight radii where stresses are most concentrated and cracks most often initiate.

Other parameters that must be controlled are shot roundness, hardness and cleanliness, shot volume, air pressure and volume, and translation of nozzles and/or workpiece (Figure 9 & 10). Type of media should also be considered carefully[16]. Most aluminum components are peened originally with steel shot for convenience, followed by a chemical decontamination to remove any residual iron. If peening is to be done locally on an aircraft, ceramic or stainless steel shot may be preferred, since they leave no active residue.

AGING AIRCRAFT APPLICATIONS

With a clearer understanding of the process, applications can be described where shot peening has been used to increase or restore the resistance to SCC & CF on aging aircraft.

a) As far back as the early 1970's, SCC was found on DC9 main landing gear attach fittings (aluminum). McDonnell Douglas required that all DC9s in service at that time be shot peened on site in the critical areas of the attach fittings. The paint and anodic coating were removed in the critical areas and energy absorbent tape applied to mask off adjacent surfaces. The general area was enclosed in plastic sheet. The shot was contained by a differential pressure peening nozzle and returned to the pressure generators for recirculation. After peening, the anodic coating and paint were reapplied. It would appear that no further evidence of cracking in these areas has been found, after the shot peening was performed.

b) In a paper entitled "Maintenance of Concorde into the 21st Century," Mr. M. J. Phillips, Senior Engineer, British Airways plc., states the following: "The power flying control unit (PFCU) cradles have caused problems in the past... The rudder PFCU cradles were reshaped using a clamp-on profile jig as a guide, and then the cradle was shot peened in situ, to improve its structural reliability"[17] (Figure 11).

c) Drawings relating to Boeing 747, "corroded lower web, wing ctr. section, stn. 1000" carry the following "Repair Procedure" (abbreviated):

"1. To inspect lower web for corrosion hidden by lower chord, refer to Boeing S.B. 747-53-2064.
2. Blend out corrosion in web...
3. Remove fasteners shown...
4. Shot peen corroded area per BAC 5730 all over blended area. Use 230-280 grade shot, .004"-.008" A-2 intensity - see ref. drg. 65B 10276 note 6 and Boeing Overhaul Manual Chapter 20-10-03 for information.
5. Alodine and paint whole of repaired area...
6. Apply sealant... to all faying surfaces.
7. ... replace removed section of chord along with splice plates and fixings."

d) There is a current Boeing specified retrofit process on all attachment lugs for the B-737-200 tail fin assemblies. The rework calls for reaming the lug bores to an oversize dimension, shot peening of the bores, followed by installing new bushings to fit. Due to the proximity of the lugs, a special tool has been manufactured to allow on-site peening of the lugs so that the fittings do not need to be disassembled from the aircraft or the fins. Sophisticated mask tooling is required to contain the shot.

The above examples are only typical of many application of shot peening used on aging aircraft to prevent of greatly retard SCC, CF and metal fatigue. The process is applicable not only to the aluminum alloys (including aluminum lithium) but also to steels (landing gears, for instance), titanium and the super alloys used in jet engines. Jet engine components, incidentally are shot peened several times for restoration of compressive stresses at periodic overhaul, usually as a protection against fretting fatigue[18] (Figure 12).

EXFOLIATION CORROSION

Exfoliation Corrosion, a more severe form of Intergranular Corrosion, occurs along aluminum grain boundaries, which in sheet and plate are oriented parallel to the surface of the material, due to the rolling process. It is characterized by delamination of thin layers of aluminum, with white corrosion products between the layers. It is often found next to fasteners where the electrically insulating sealant or a cadmium plating, for instance, has broken down, permitting a galvanic action between the dissimilar metals. Where fasteners are involved, the corrosion extends outward from the fastener hole, either from the entire circumference of the hole, or in one direction from a segment of the hole, In severe cases, the surface bulges upward, but in less severe cases, there may be no telltale bulging, and the corrosion can only be detected by nondestructive inspection methods,[19 & 20] (Figure 13 & 14).

Controlled shot peening is of little value in preventing Exfoliation Corrosion but it can be very effective in the process of repairing the damage. Service manuals normally call for the removal of the fasteners and then for the use of rotary files to grind away the corroded material followed by blending the area and polishing out the tool marks. Aircraft engineers have used controlled peening after polishing to increase the fatigue strength of the newly reduced cross-section. The action of the peening can cause the surface to bulge out again where deeper exfoliation has taken place. The surface can then be reground and repeened until no further bulging occurs. The shot peening provides excellent NDT of the exfoliated material. The action of the peening on the thin exfoliated layer is essentially the same as that employed in the process of peen forming, used to generate the aerodynamic curvatures in the wing panels of most commercial airliners[21] (Figure 15). Peening of corroded surfaces can be accomplished using special enclosures to contain the media (Figure 16). It is essential to maintain extreme control on the intensity of the peening not to cause bulging of the skin itself, rather than just the exfoliated layer, which would scrap out the entire panel. A patent has been applied for a "wing walker" machine which is used to undertake "search peening" for exfoliation corrosion along the rivet lines on the wing surfaces.

PEEN FORMING

Boeing Service Bulletin 737-57A1081 covers the repair of left and right wing chords on B-737 aircraft. To repair the chord, it is necessary to remove a wing skin panel that is approximately 10 inches wide by 120 inches long. The replacement panel is essentially flat and does not fit the contour of the wing. To restore the contour, after the trailing edge of the panel is secured, the Service Bulletin instructs as follows:

"5. Shot peen designated area per Boeing Standard Overhaul Practices 20.30.03 or operator's comparable procedure... using cut stainless steel wire shot at <u>coverage and intensity sufficient to bring spring-up value(s) to less than 0.03 inch."</u>

Implied (but not stated) is that these panels must be peened formed on the aircraft, a procedure that requires considerable experience and skill: any distortion or even over-forming cannot be corrected, once it has happened (Figure 17).

CONCLUSION

Well established techniques of controlled shot peening, as used on aircraft components at the manufacturing stage, are being applied to aging aircraft in the field to prevent or retard failures from fatigue, stress corrosion cracking, corrosion fatigue, fretting, etc., by the introduction of high magnitude compressive stresses. Peening is also being used to identify and combat the effects of exfoliation corrosion.

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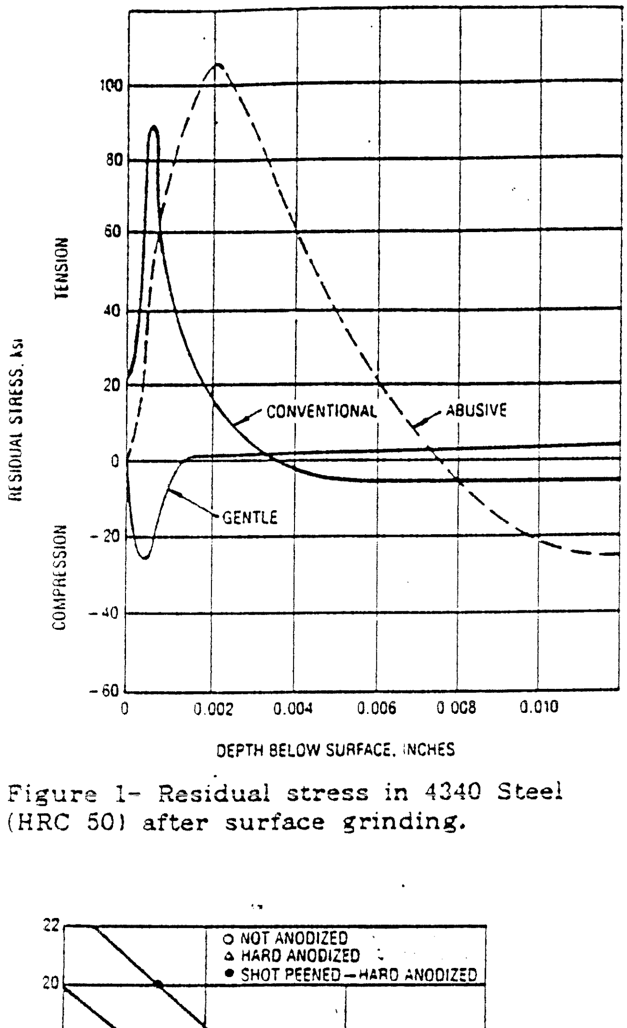


Figure 1- Residual stress in 4340 Steel (HRC 50) after surface grinding.

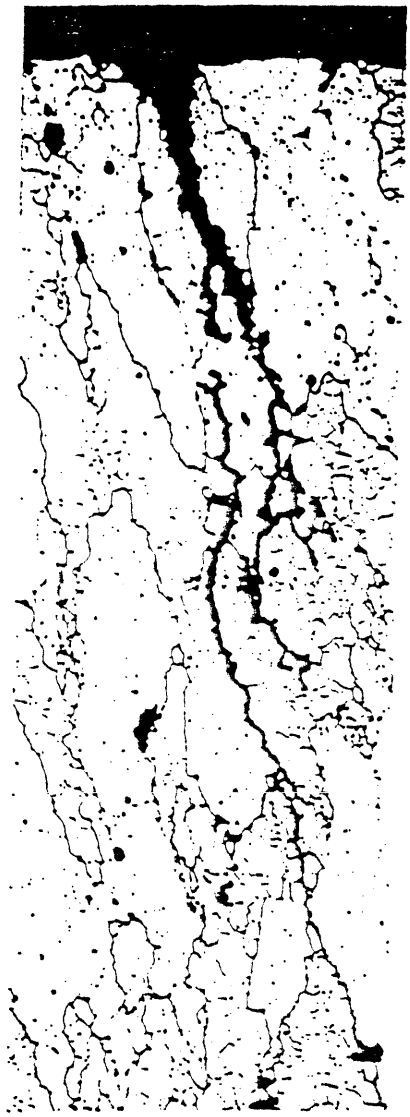


Figure 2- Photomicrograph of crack found in a 7079-T6 forging, 500X.

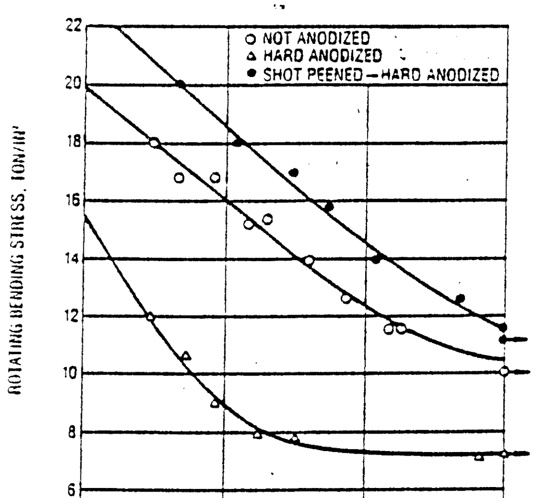


Figure 3- The influence of hard anodizing and shot peening on the failure strength of Duralumin (LI).

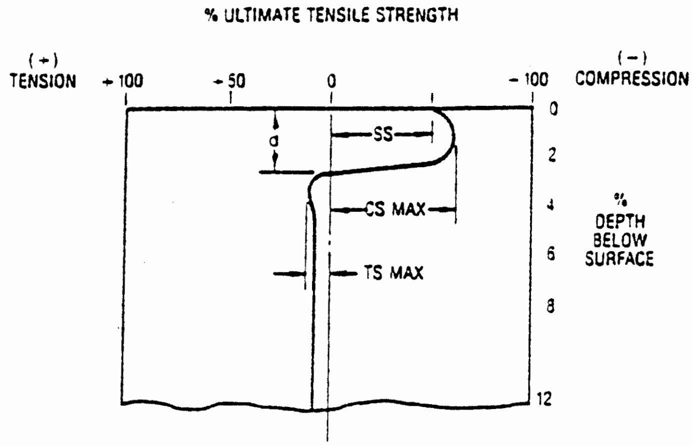


Figure 4- Example of Residual stress profile created by shot peening.

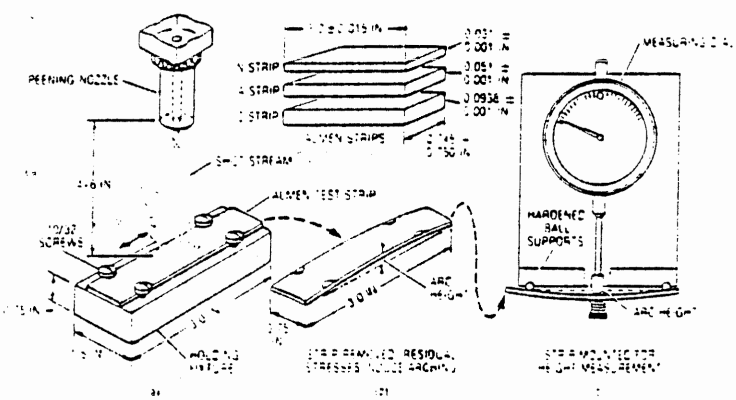


Figure 5- The Almen Intensity determination system.

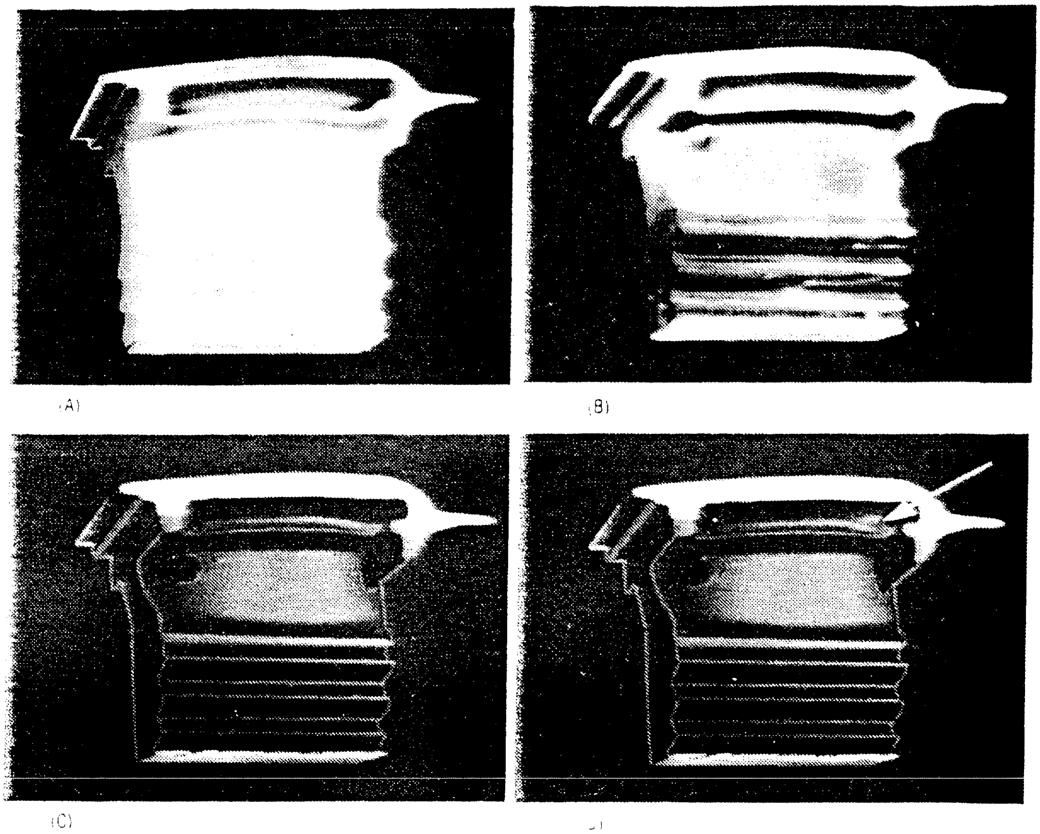


Figure 6- The Peenscan[3] System. (A) Coated, unpeened. (B) Peened 15 seconds, partial coverage. (C) Peened 60 seconds, improper nozzle angle in cavity (arrow).

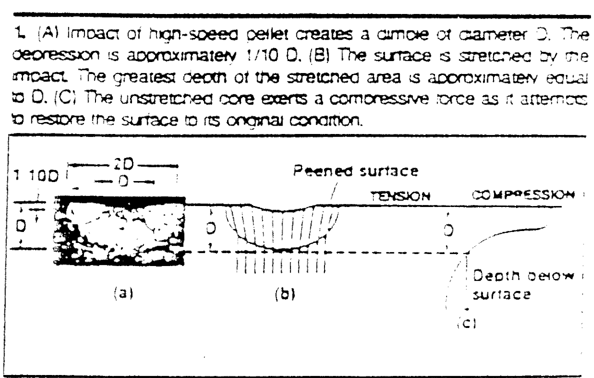
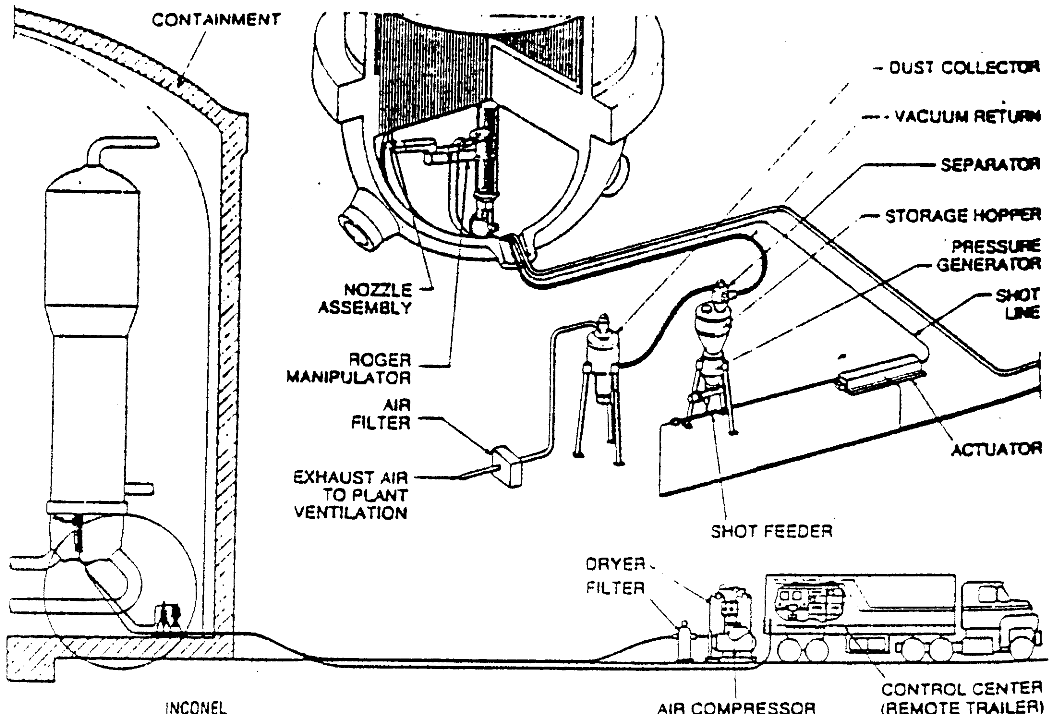


Figure 7- Schematic of residual compressive stress created by a single shot peen dimple.



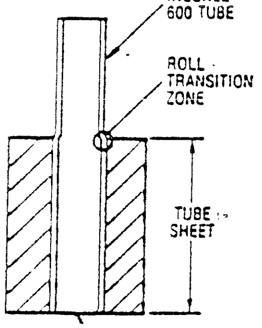


Figure 8- Schematic of computer controlled shot peening equipment used inside of containment at nuclear power stations. Insert: SCC failure location at roll transition zone, approximately 600mm (24 inches) inside 20mm (3/4 inch) diameter steam generator tubes.

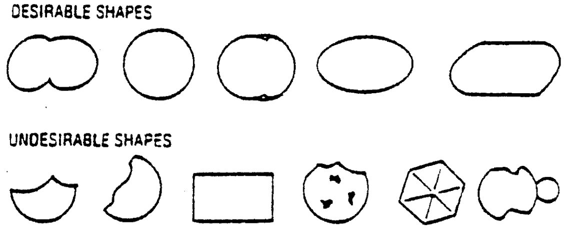
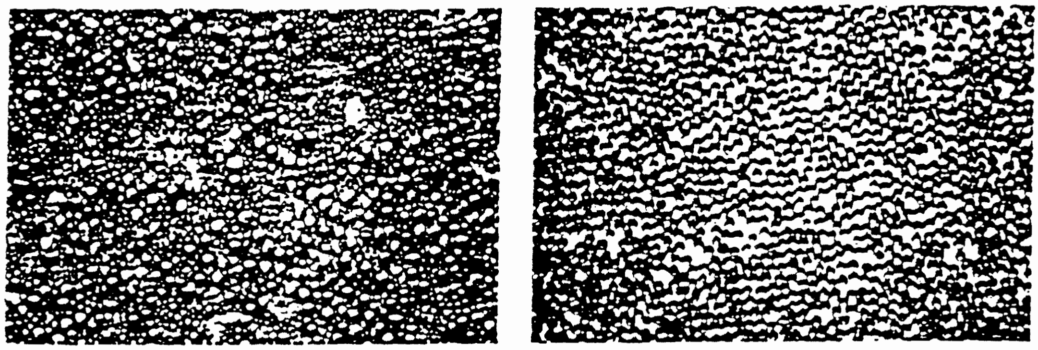


Figure 9- Peening media shapes.



(A) (B)

Figure 10- (A) Unacceptable shot peening media. (B) Acceptable shot peening media.

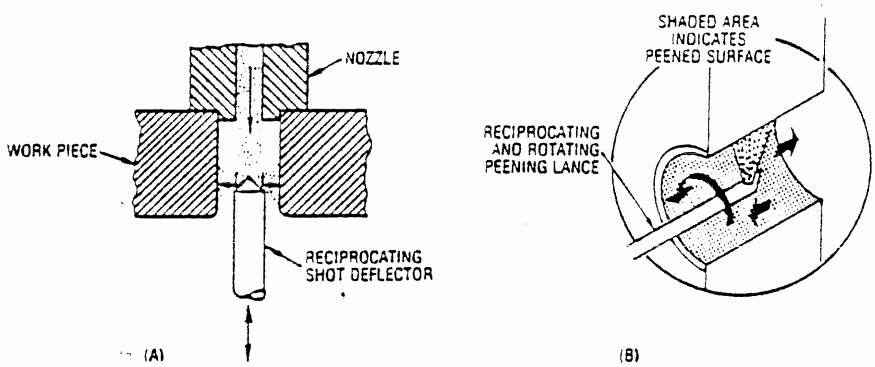


Figure 11- Shot peening of holes using deflector lance nozzle.

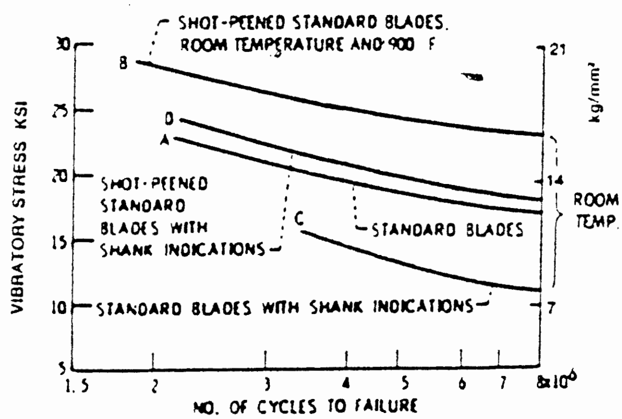


Figure 12- Suppression of fatigue damage of Inconel 713C turbine blades by shot peening.

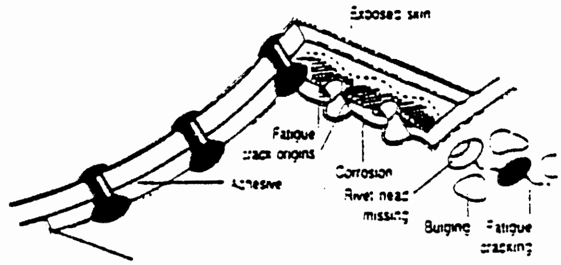


Figure 13- Exfoliation corrosion, which shows as bulges around rivet heads, can propagate into fatigue cracks.

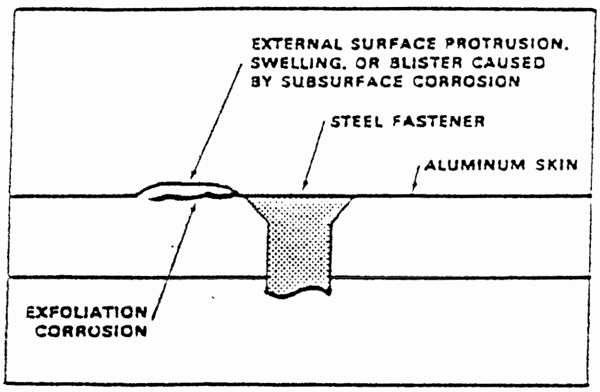


Figure 14- Section through typical exfoliation blister or protrusion.

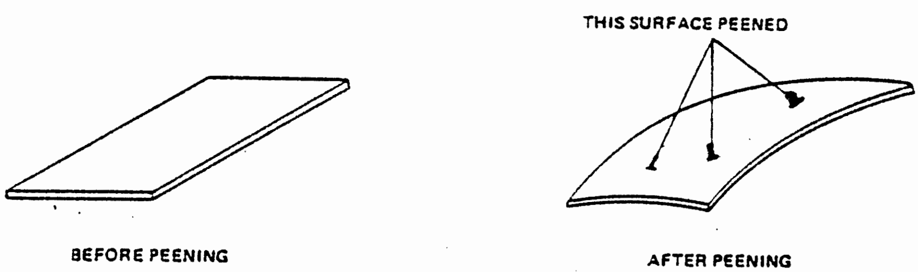


Figure 15- Compound curvature resulting from tri-axial forces induced by shot peening.

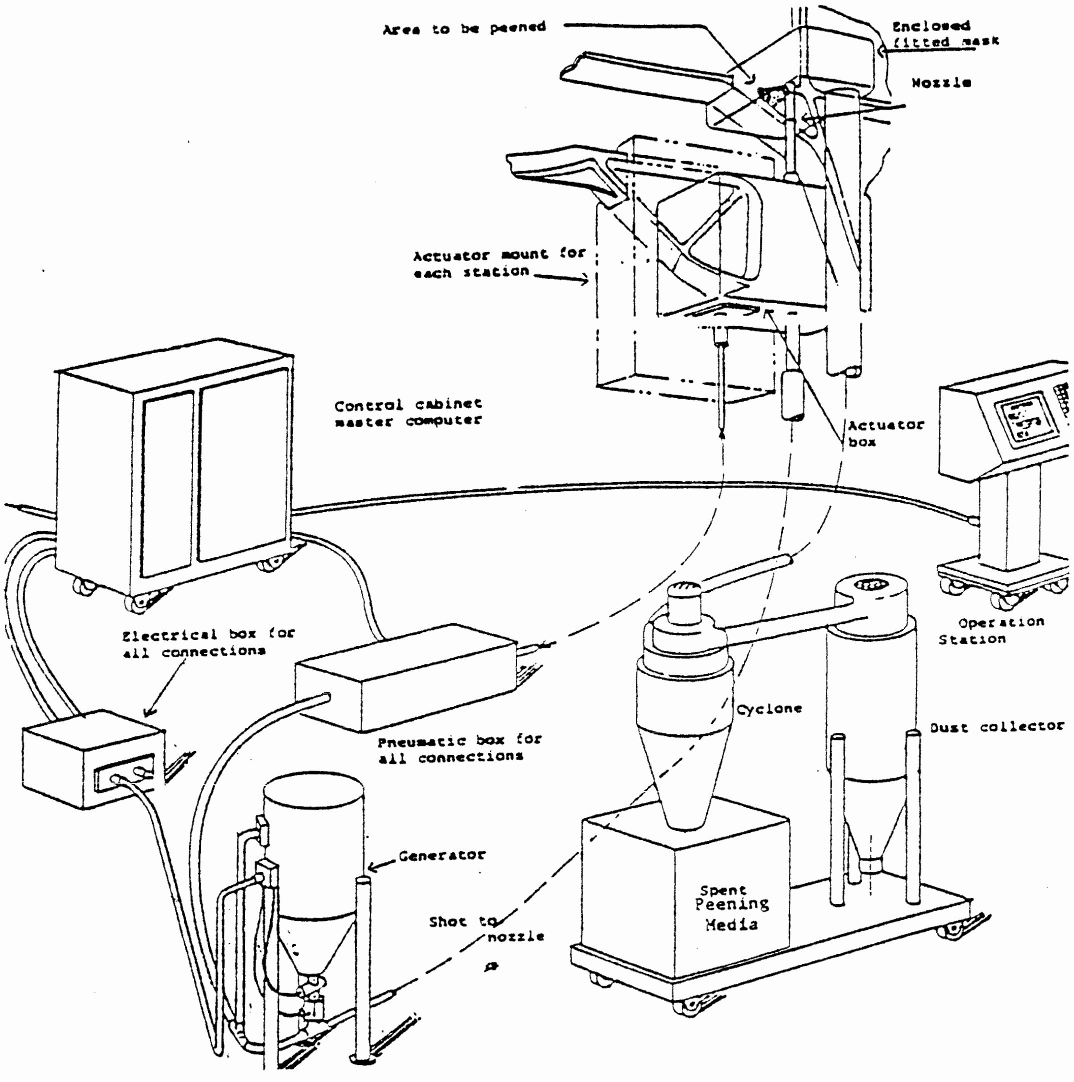
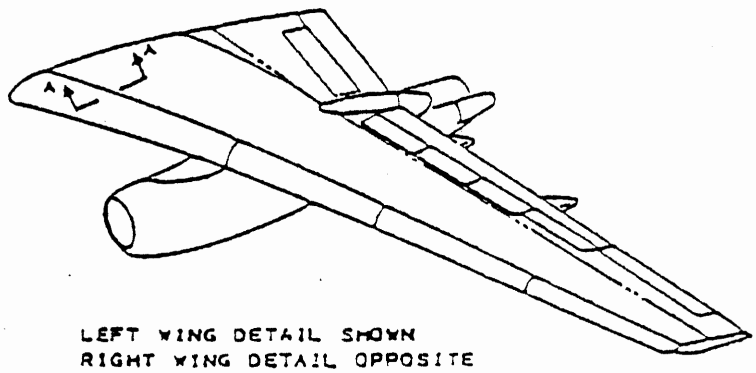
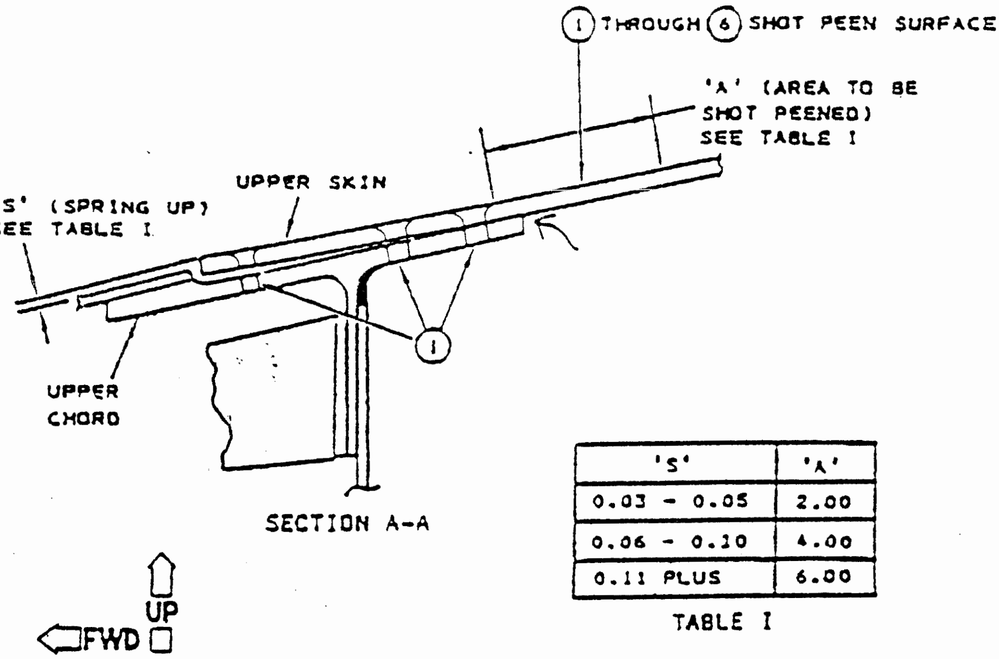


Figure 16- Schematic of computer controlled system for on-site shot peening of aging aircraft structures.

BOEING SERVICE BULLETIN 737-57A1081





'S'	'A'
0.03 - 0.05	2.00
0.06 - 0.10	4.00
0.11 PLUS	6.00

TABLE I

FIGURE 1.7 WING SKIN SURFACE SHOT PEENING REQUIREMENTS AT FRONT SPAR UPPER CHORD

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