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USING SHOT PEENING TO MULTIPLY THE LIFE OF COMPRESSOR COMPONENTS

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ABSTRACT

Fatigue life increases, by orders of magnitude, can be expected on compressor components treated by Shot Peening — a controlled process that involves the bombardment of the metal component by millions of spherical particles of steel, glass or ceramic. Shot Peening is being applied to crankshafts and con-rods of huge reciprocating compressors and to the small valve reeds, only a few thousands of an inch thick, that are the heart of refrigeration and air conditioning sealed units. In what is perhaps the "ultimate" in design of axial and centrifugal compressors, the modern jet engine, Shot Peening is used on all rotating parts, as well as many of the stationary ones, to prevent premature failures from metal fatigue, corrosion and fretting fatigue, and from stress corrosion cracking.

The paper reviews these and other applications for compressor engineers so that they will be able to increase the life and/or the loading on both new and existing designs, without increasing size or adding weight to critical components. The controlling parameters of the Shot Peening Process are also discussed.

HISTORICAL BACKGROUND

Shot Peening was first used, in a production application, to extend the life of the valve springs for the Buick and Cadillac engines of the early 1930's (Ref. 1). The process was discovered accidentally and, although the benefits were soon recognized, it was several years before a mechanism was proposed and even longer before is was generally accepted. It was recognized, at the time, that fatigue cracks initiated under repeated tensile loads. John Almen postulated that Shot Peening produced the increases in fatigue life from the introduction, of a high residual compressive stress, which remained just below the surface of the part (Fig. 1, Ref. 2). Any applied tensile loads, affirmed Almen, would have to overcome this residual compression before a crack could start. Furthermore, Almen claimed that many parts (springs, for instance, from the coiling operation) had in them, from manufacturing, residual tensile stresses, that when added upon by the tensile loads, would further contribute to the part's early failure. Shot Peening, he said, reversed the surface residual stress from tension to compression, accounting for the very great improvements in fatigue life that are typical of the process. The academic community was almost totally opposed to John Almen's theories since, at the time, the presence of residual stresses in metals was not recognize in engineering calculations. The advent of Fracture Mechanics eventually vindicated Almen's position. Today, we not only recognize residual (or self) stresses; we are able to measure them with a considerable degree of consistency, primarily by x-ray diffraction.

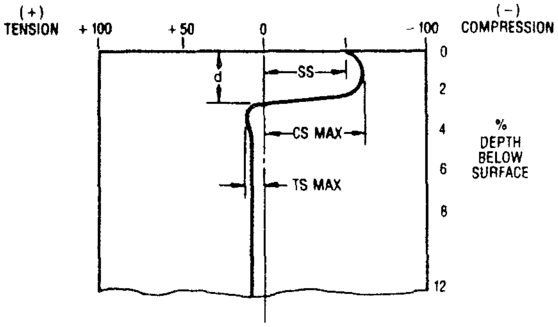

FIGURE 1. EXAMPLE OF RESIDUAL STRESS PROFILE CREATED BY SHOT PEENING.

Consideration Of Residual Stresses

If the part is dimensionally correct, are residual stresses all that important, in a fatigue application? A very current case is an excellent illustration. A group of engineers are developing a torsion bar for a space application (the exact nature is "classified"). They carefully ground the test torsion bars to produce the final profile and a smooth surface. The unpeened torsion bars, at the applied load level, averaged close to a million cycles to failure and the stress analyst in the group figured from this information, that shot peening would about double the life of the bars, to two million cycles: sufficient for the application. To his surprise, the first (and only) Shot Peened torsion bar that they tested ran for 166 million cycles when the test was discontinued.

In most applications for Shot Peening, the benefit obtained is the direct result of the residual compressive stress produced. A typical profile of residual compressive stress as it changes with depth is shown. It has four important characteristics:

1) SS - Surface stress - The stress measured at the surface. (2) CS max - Maximum Compressive Stress - The maximum value of the compressive stress induced, which normally is highest just below the surface. (3) d - Depth - The depth of the compressive stress is the point at which the compressive stress crosses over the neutral axis and becomes tensile. (4) TS max - Maximum Tensile Stress - The maximum value of the tensile stress induced. The offsetting tensile stress in the core of the material balances the surface layer of compressive stress so that the part remains in equilibrium. TS max must not be allowed to become large enough to create early internal failures.

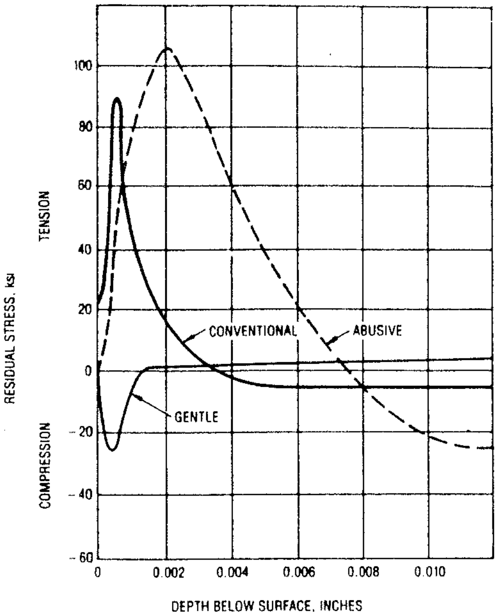

FIGURE 2. RESIDUAL STRESS IN 4340 STEEL (HRC 50) AFTER SURFACE GRINDING.

Graph shows the stress distribution created by different grinding techniques - conventional, abusive and gentle. It is quite evident that conventional grinding and abusive grinding can generate high magnitudes of residual tensile stress at or near the surface of the parts. This tensile stress will, of course, dramatically affect fatigue resistance.

The stress analyst had based his calculations on the assumption that the unpeened torsion bars were in a "neutral" state of stress before any loads were applied. In reality, the grinding operation had introduced residual tensile stresses, which in extreme cases can actually exceed the yield strength of the metal (Fig. 2, Ref. 3). The failures at a million cycles were actually premature failures caused by the debiting effect of the grinding stresses. When the bars were Shot Peened, the surface residual stresses were reversed, from close to the yield strength in tension to close to the yield strength in compression or a delta, in this case, of over 300 KSI. The Shot Peening actually raised the endurance limit of the torsion bars well over the stress level applied in the testing, contributing to virtually infinite life. Not all applications of Shot Peening are so dramatic, but this is a good reminder that residual stresses, detrimental or beneficial, should not be ignored.

Realizing that the Purdue Conference is directed almost exclusively at engineers involved with small compressors for refrigeration and air conditioning, we thought it would be useful to review, quite briefly, some of the applications of the Shot Peening process in the very large or very different compressors that are found in other industries, since much can be learned from them. Then, we want to be more specific in discussing the benefits of Shot Peening for valve reeds and rings since our unique success in this area has propelled Metal Improvement Company to become one of the leading manufactures of these very critical components.

SHOT PEENING FOR INDUSTRIAL AND AIRCRAFT COMPRESSORS

Reciprocating Compressors

1. Crankshafts are most commonly peened in the fillets of the pins and mains to produce increases in fatigue strength of up to 30%. Crankshafts have also been peened in the oil holes and keyways (Fig. 3, Ref. 4).

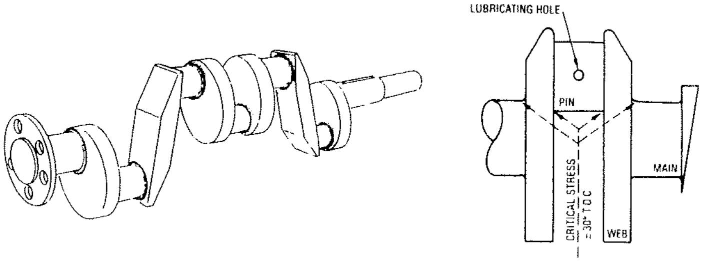

FIGURE 3. INCREASE IN FATIGUE STRENGTH OF SHOT PEENED CRANKSHAFTS.

The most highly stressed area of a crankshaft is the crank pin bearing fillet. The high stress point is the bottom side of the fillet when the pin is in the top dead center position during the firing cycle. It is common for cracks to initiate in this pin fillet and propagate through the web of the crankshaft to the adjacent main bearing fillet, causing fatigue failure. All sizes of crankshafts respond well to shot peening, from small high speed shafts with journal bearing diameters of 1", to large slow speed shafts having journal bearing diameters of 6" and more. Experience has shown the process to be effective on forged steel, cast steel, nodular iron, and austempered ductile iron.

2. Connecting Rods are usually peened prior to machining, to prevent fatigue failures in the I-beam section but some large ones are also peened in the oil holes and in the fillets by the bolts. Fretting fatigue is prevented by peening the serrations between the rod and the cap, the bearing surfaces, and the bolt holes.
3. Connecting Rod Bolts are shot peened for axial fatigue in the shank to head fillet and for fretting fatigue in the shank itself. Sometimes, the thread roots are peened, which can impart to a cut thread almost the same fatigue strength as a rolled thread.
4. Tie-Rod Bolts are used in very large compressors to hold the assembly together or are used just around the cylinder heads. These bolts are peened for the same reasons as the connecting rod bolts described above.
5. Tail Rod Cylinders are peened at the intersections of crossbores to prevent crack initiation.
6. Hyper Cups are used to hold the seal around the push rods of very high pressure (approaching 50,000 PSI) compressors. The Shot Peening retards failures from bending and fretting fatigue.
7. Ring and Strip Valves are edge finished and peened for very high cycle fatigue.

Centrifugal Compressors

Impellers have been Shot Peened that range in size from less than 2 inches in diameter for a space application to 48 inches for process air. Turbochargers fall under this classification and many are shot peened against blade failure. One unique application involved thermal cracking at some locating serrations on the back face of aluminum impellers for locomotive diesel turbochargers. Of concern was the heat that might relieve the compressive stresses form Shot Peening. However, peening solved the problem, using glass beads to avoid ferrous contamination of the aluminum.

Most of the smaller turbines employed in aircraft, sometimes for propulsion, but most often as auxiliary power units, air starters, etc., use Shot Peened impellers, as do the engines for the Cruise Missile. Significant weight reductions are possible by including the benefits of Shot Peening in the design calculations. Materials for impellers, incidentally, may be sand cast iron or aluminum, welded steel, forged aluminum or titanium; even investment cast superalloys: all respond well to Shot Peening.

Axial Compressors

Many are used in stationary applications (a good one is for making snow on the ski slopes), but most axial compressors are used in combination with a gas turbine to form a jet engine and provide propulsion for planes, boats and trains, and some experimental trucks. Because of the extreme centrifugal, axial and vibrational forces acting on the rotating components, all shafts, disks and blades are typically Shot Peened against bending and fretting fatigue. In fact, there are very few components of a high performance jet engine that are not peened, both during original manufacture and again at periodic overhaul intervals, and include less obvious components such as gears and fuel lines.

Diaphragm Compressors

Diaphragm compressors are quite uncommon and are used in applications where absolutely no contamination (from lubricating oils, for instance) of the compressed gas is permitted. The critical component is a large (up to 30 inches diameter by 0.030 inch thick) stainless steel diaphragm that is clamped around the edges in the compressor head. Because the diaphragm moves up and down under hydraulic pressure, cracks initiate just inside of the bolt hole ring. Typically, a chemical company, compressing Freon, used to replace these diaphragms every 16 hours of service. Peening the diaphragm with glass beads (on stainless steel) extended the service life to 6 months. The difficulty here is to peen the large but very thin diaphragm and still maintain flatness: exactly the same problem that is encountered in peening the small valve reeds with which you are all familiar.

COMPRESSOR VALVE COMPONENTS

To quote D.N. Lal, Research Engineer at the Carrier Corporation: "The valve, suction or discharge, is one of the most critical components of a compressor. A flapper valve is required to have high flexibility to allow unrestricted fluid passage through the ports for achieving high efficiency and capacity of the compressor, but at the same time it is also expected to have enough stiffness to return back in time to seal the ports completely. The motion subjects the valve to severe cyclic stresses and strains. To make the situation worse, most of the valves have irregular geometry as unavoidable design requirements. This increases the possibility of localized stress concentration and premature failure by fatigue" (Ref. 5). Few would dispute Lal's statement, but it leaves the designer of a compressor with having to make a serious compromise between the efficiency of the compressor and the life of the valve. The more the flapper reed flexes, the more passage of fluid it will permit but the shorter will be the number of flexures the flapper will sustain before breaking. It is incumbent on the designer to seek a reed that will allow the maximum passage of fluid without breakage during the expected life of the compressor at, let's not forget, a cost that is within budget.

The geometry of the reed is usually the first consideration and one over which the manufacturer of the reed has little control. Actually, the designers are much better served if they include the manufacturer at an early stage of the design. A manufacturer of reeds should not just be able to stamp out metal shapes: he must thoroughly understand all the factors that influence the life expectancy of a valve. For instance, the diameter of a mounting hole or the width of a slot, within obvious limits, may have little influence on the efficiency of a reed but they can create difficulties for the reed maker that will impact both on the life and the cost of a reed. The reed maker must have a complete knowledge of materials; stresses (applied and residual; beneficial and detrimental); how life is affected by edge geometry, surface conditions, heat and corrosion; and the influence of bending, torsion and impact loads. Because his speciality is valves (and not compressors) the reed manufacturer can be of great value to the designer.

The ideal valve reed would open fully and close totally in zero time: and last forever. We certainly are not there yet but an evolving technology, based on a more complete understanding of the many phenomena involved, is taking the best reed makers ever closer. We know that there are at least five areas that must be given attention: 1. Choice of material, 2. Stamped edges, 3. Removal of defects and detrimental stresses, 4. Edge rounding, 5. Depth and magnitude of beneficial stress. We will address each of these items individually but it must be remembered that all are very much interrelated. For instance, maximizing #5, in theory would allow the use of thinner steel (#1) so that the reed would flex more and faster but maintaining flatness could then become a difficulty that would compromise the reed's ability to close totally. Overcoming this difficulty is the province of a good reed maker and much has been done in this area. Pursuing all of the above items to the maximum of current technology will produce a reed closest to the ideal. The extent of this pursuit is governed by the cost considerations of the application and the degree of efficiency that the designer wishes to obtain for the compressor. Designers need to be aware of the options available to them.

Choice of Material

There is much information published by the suppliers of valve steels and it is not our province to review it in detail. High carbon strip is the choice for thin reeds and is supplied and stamped in the pre-hardened condition. Nickel-alloyed steel is usually used for thicker valves and hardened after stamping. Stainless is preferred for applications where corrosion can be a problem (Fig. 4, Ref. 6), such as in the presence of air, water or steam, dilute organic acids and sulphurous fumes. A corrosive environment will always lower fatigue properties, even in stainless steels, but the effect can be largely over come by the introduction of high residual compressive stresses.

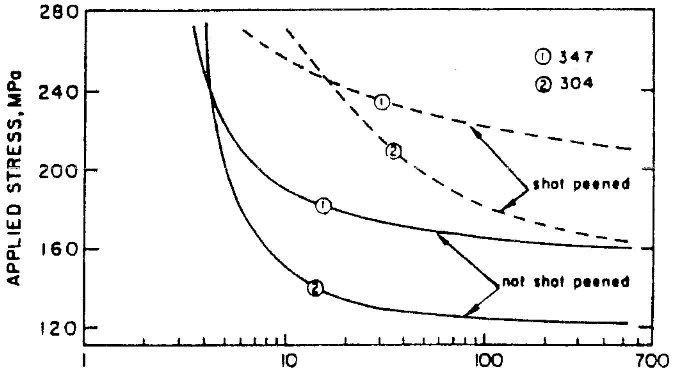

FIGURE 4. STRESS CORROSION CRACKING.

Effect of Shot Peening with 40-80m glass shot on the times to failure to type 304 and 347 stainless steels in a boiling 42% magnesium chloride solution.

Stamped Edges

A fatigue failure will always nucleate at the point of greatest stress concentration: sometimes at an inclusion in the steel, but in the case of valve reeds, almost always at a surface defect created by the stamping operation (Ref. 7). All subsequent operations, i.e., edge rounding, removal of defects and introduction of beneficial stresses, are all performed primarily to remove or offset these surface defects from stamping. The technology of producing good reeds is totally tied to the technique of producing stamped edges that are as free from defects as possible. The importance of this will become more apparent as we look at the subsequent operations.

Removal of Defects and Detrimental Stresses

There are a variety of processes available to the reed maker to, essentially, wear away the stamped edges and smooth out the stress concentrating defects. All are very time-consuming (and cost raising) and have limitations, especially from reed geometry. For instance, rough edges of narrow slots and small holes are very difficult to smooth out without loosing dimensions on the more exposed edges. Starting with stamped edges that are essentially free of defects is paramount here. Also, the stamping operation introduces residual tensile stresses at the edges of the reed. A good finishing process, such as STRESS-LITE, (Fig. 5, Ref. 8) will reverse these detrimental residual tensile stresses into beneficial compressive stresses but, again, starting with a near perfect stamping makes the stress reversal process not only more effective but, in some cases, even possible.

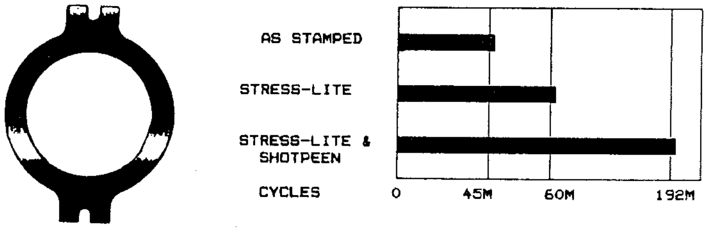

FIGURE 5. LCF OF SUCTION VALVE, IN THREE CONDITIONS.

The bar chart shows the performance of a particular valve for which filed failure data have been statistically related to a low cycle/high stress condition, thereby permitting accelerated life testing. This suction valve is used in an air conditioning hermetic compressor.

Edge Rounding

Bending and torsional stresses are concentrated not only by notches (surface defects) but also at sharp outside corners. Therefore, even if we had a theoretically perfect stamped edge, it would still be necessary to use processes that will round the edges and distribute the applied stresses over a greater area. Here, again, the quality of the stamped edge is key: to the degree that the as-stamped edge is smooth, less edge-rounding is necessary. Too much edge finishing can produce a taper in the thickness of the reed on the sealing surface so that the reed will not close off the port. This may be difficult or even impossible to prevent if large defects from stamping must be removed in narrow slots to avoid fatigue.

Depth and Magnitude of Compressive Stresses

Compressive stresses can be introduced by the correct edgefinishing process. They will be very shallow and of relatively low magnitude but, in many cases, are sufficient for the application, particularly if the stamped edges are near-perfect.

Shot Peening will, as we have seen in the earlier sections of this paper, introduce much deeper residual compressive stresses and of a magnitude approaching the yield strength of the steel. It does so by indenting the surface so that the compressive stress is created in the subsurface layer that can be thought of as trying to push the indentation back out again. The magnitude of this compressive stress, then becomes a function of the yield strength of the material, as long as the surface is totally indented. As far as fatigue is concerned, the higher the magnitude of residual compression, the higher the fatigue strength and the longer the life of the reed. However, surface defects or discontinues always have a debiting effect on fatigue life, particularly if any are deeper than the layer of residual compressive stress (Fig. 6).

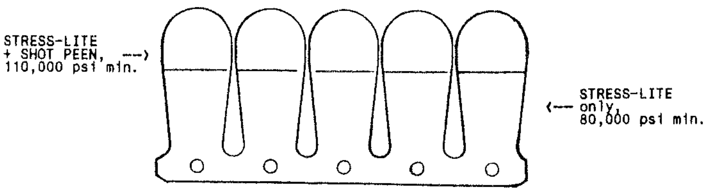

FIGURE 6. STRESS-LITE AND SHOT PEENING.

STRESS-LITE is a proprietary process developed to control edge radius, improve surface finish and to induce a high magnitude of residual compressive stress for increased fatigue life. The illustration is of a 2-cycle outboard engine reed blanked out of stainless steel, which has a drawing requirement for a minimum of 110,000psi at the tips and 80,000 psi compression on the balance of the reed. STRESS-LITE is used to process the entire reed to yield residual stresses as high as 97,000 to 99,000 psi. Addition of Shot Peening to the tips increases the surface residual compressive stress to as much as 132,000 psi.

On a relatively thick part, say a quarter inch (6mm) or more, it is quite easy to peen to a depth of 0.010 inch (0.25mm) to get below surface discontinues. Peening very thin valve reeds is an entirely different proposition and there are two interconnected concerns: distortion and internal stresses. Metal Improvement Company actually uses a controlled distortion (Peen Forming) to produce the aerodynamic curvatures on aircraft wing skins that can be as much as an inch (25mm) thick and 110 feet (34 meters) long (Ref. 9). Effectively Shot Peening reeds that may be only 0.06 inch (0.4mm) thick while holding acceptable flatness tolerances, requires unusual techniques. Beyond the distortion, though, consideration must also be given to internal tensile stresses. Putting the surface into compression always produces a corresponding tensile stress in the core of the metal. If the depth of compression is too deep relative to the thickness, the core tensile stresses can become high enough to cause subsurface fatigue failures and shorten valve life (also see Fig. 1). Critical control of the depth of compression can be exercised by intelligent use of the Almen Intensity System (Ref. 10). Peenscan^R, a fluorescent tracer, is used to determine when 100% coverage has been reached (Ref. 11). These and other tools and techniques are applied today to gain great improvements and repeatability in the fatigue life of modern valve reeds.

CONCLUSION

Controlled Shot Peening is used very effectively in the manufacture of many components of both large and small compressors. Very significant increases in life of valve reeds and rings can be achieved with Shot Peening, but it must be used in combination with advanced techniques for stamping and edge finishing, as well as correct choice of material.

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