Most manufacturers of heavy equipment currently make extensive use of the shot peening process to compensate for the increased operating stresses imposed by upgrading designs.

The effect of residual stresses on the fatigue performance of highly stressed parts is well known, and unfortunately, it is not always easy or even possible to control the introduction of unfavorable residual stresses during the manufacturing operations. The high magnitude residual compressive stresses produced by controlled shot peening can result in significantly longer fatigue life for engine and other power train components.

The prime purpose of the shot peening process is to improve the fatigue strength of metals, although there are many other applications of the process where residual stress is the key to solving a problem.

Shot peening is a cold working process which produces a shallow layer of high magnitude residual compressive stress at surface. This is accomplished by bombarding the surface of the part with spherical steel balls impelled at high velocity.

The magnitude of the compressive stress produced by cold working is a function of the ultimate tensile strength of the metal and may reach values as high as 50-60% of U.T.S. In the case of high strength steels, the hardness of the peening shot will have significant effect on the magnitude of the residual stress. Since we are depending on the peening shot
Consequently, when the part is placed in service, it will experience and of high magnitude, regardless of the surface residual stress prior to shot peening, and will be uniform. For these applications, a special hard shot in the range of 55-65Rc should be used to maximize the effect of the peening. In residual stress studies performed on steel in the 60Rc range, it was determined that the residual compressive stress obtained by using special hard shot, was roughly double that produced by using regular hardness shot.

The depth of the residual compressive stress produced by peening is a function of both the tensile strength of the material and the intensity of the peening, or in other words, the kinetic energy imparted to the surface of the part. In relatively soft metals, 20-30Rc, it is feasible to produce a compressive layer of .030-.040 inch. However, in the harder surfaces in the range of 60Rc, it is difficult to produce a compressive layer of much more than .008-.010 inch.

The effect of a particle of peening shot striking the surface of a part at high velocity, is that of creating a depression in the surface. We call this indentation a dimple. In creating the dimple, the outer surface has been yielded in tension. The area immediately below the surface has been stressed but unyielded, and remains in the stressed condition. This stress which opposes the stress that caused surface tensile yield, is therefore compressive in nature. There are several factors relative to metal fatigue:

1. The surface of the part is the most susceptible to fatigue and most fatigue cracks initiate at surface.
2. Fatigue cracks initiate in an area of tensile stress.
3. Many manufacturing operations leave the surface in residual tensile stress.
4. A fatigue crack will not initiate in, nor propagate into a compressively stressed area.

It then becomes apparent that if the surface of the part is shot peened, the surface residual stresses will be compressive and of high magnitude, regardless of the surface residual stress prior to shot peening, and will be uniform. Consequently, when the part is placed in service, it will have significantly longer fatigue life. In this case, shot peening has extended the life of a part which may have been experiencing premature failure. On the other hand, as often happens, it is desirable to use an existing design at higher stress levels due to additional power needs, etc. Shot peening of the critical fatigue areas will allow this design to be used at higher stress levels and still exhibit acceptable life.

Because the magnitude of residual compressive stress produced by shot peening is proportional to the U.T.S., peening is usually more effective on the higher strength materials. In the case of through hardened steels, the fatigue resistance will generally be reduced with increased hardness beyond approximately 40Rc due to increased notch sensitivity in the higher hardness levels. However, shot peening these higher hardness steels will have the effect of negating the increased notch sensitivity and allow these materials to be used at much higher stress levels in a fatigue environment. A typical example of this concept would be a component which is failing in fatigue as a result of a relatively low number of high stress cycles. Peening this component, as the only solution, would probably not solve the problem as peening is normally not extremely effective in high stress low cycle fatigue. The reason for this is, that in a low cycle failure, the part is probably being stressed at a level close to the yield strength of the material. When the applied stresses reach these high levels, they tend to yield or partially yield the residual stresses produced by the shot peening. The probable solution in this case would be to heat treat the material to a higher hardness, followed by shot peening. By increasing the hardness and consequently, the yield strength of the material, the applied stresses then become a smaller percentage of the yield strength and there is less tendency to affect the peening stresses.

Earlier it was mentioned that manufacturing processes can have a detrimental effect on fatigue performance. This can result from introduction of residual tensile stresses or other factors inherent to the processes. Some of these are as follows:

1. Grinding-Severe grinding operations have been shown to produce severe residual tensile stresses in the surface of the metal. Even in the case of grinding "burn" and grinding "check", shot peening has been shown to be
capable of negating the detrimental fatigue effects.

2. Heavy Machining - Heavy Machining operations such as turning, milling, etc., can have two adverse effects on fatigue. It is possible or even probable, that residual tensile stresses will be produced by the heavy machining, and almost certainly, it will result in a poor surface condition with resulting stress concentrations. From the standpoint of residual tensile stress, shot peening will change the residual stress to compressive stress, and by controlling the depth of the compressive layer through intensity, the depth of the layer will exceed the depth of machining marks and negate the effect of the stress concentration.

3. Welding - The effect of welding on the fatigue strength of a part is well known. The heat-affected zone on either side of the weld area will contain residual tensile stresses, many times of high magnitude. If this part is subjected to dynamic loading, the fatigue cracks will initiate in the area adjacent to the weld. Thermal stress relief may be effective, although it is questionable whether the tensile stresses are completely relieved. The best practice in these cases is to thermally stress relieve, followed by controlled shot peening.

4. Hard Plating - Hard chrome and electroless nickel plating are notorious in their adverse effect on the fatigue strength of metals, particularly when the base material is above 40Rc. In either case, a thin layer of hard, brittle material is deposited on the surface of the part. If this part is dynamically loaded, cracks will initiate in the plating because of its brittle nature. These cracks serve as points of stress concentration and the cracks will then propagate into the base material, eventually causing failure. Testing has shown that chrome plating of fairly high strength steels (52-53Rc) has resulted in a reduction of fatigue strength by as much as 50%. By shot peening the surface of the part prior to a hard plating operation, the detrimental effects of the plating can be negated. The cracks will still develop in the plating material but will not propagate through the compressive layer.

There are other manufacturing processes such as EDM and ECM which are detrimental to fatigue strength but those mentioned above are the most common offenders.

There are, of course, other manufacturing operations which result in improved fatigue characteristics. Some of the more common of these are rolling, burnishing, shot peening, carburizing, and induction hardening. The first three mentioned are cold working processes, all resulting in surface compressive stresses. Of these, rolling and burnishing are severely limited as to part geometry and tool geometry and are usually difficult to control because of these factors.

Carburizing and induction hardening also produce compressive stresses in the surface of the part through heat treatment. However, in both cases, the magnitude of compressive stress is relatively low compared to the residual compressive stress that can be produced by shot peening the surface of these parts after they have been given the respective heat treatments.

It is common practice to shot peen both carburized and induction hardened parts to take advantage of the best of both processes. In the case of either of the heat treating processes, a relatively deep layer of compressive stress is produced in conjunction with the surface compressive stresses. Shot peening then produces a thin layer of much higher compressive stress at the surface, further enhancing the fatigue resistance.

The applications of shot peening in the heavy equipment manufacturing field are numerous, ranging from many engine components, spring suspensions, transmission components, differential and axle parts, to hydraulic cylinder components. As a general comment, it might be said that most metal parts which are dynamically loaded can have their life extended by shot peening. There are several typical classes of parts which immediately come to mind. The first of these is springs. Perhaps the earliest commercial use of shot peening dates back to automotive valve springs in the late 1920's and early 1930's.

Often a spring will be among the last components designed for a mechanism, and its design is limited by the space allocated to it in the overall design. Springs probably respond more dramatically to shot peening than any other machine component. For example, a compression spring will show as much as 60 to 70 percent improvement in fatigue strength as compared to an unpeened spring. While compression
springs seem to show the greatest improvement, they are also the most difficult spring to peen properly. The most highly stressed area of a compression spring is the I.D. of the coil and this is also where the highest residual tensile stresses from the coiling operation occur. Consequently, it is imperative that full intensity and peening coverage occur on the I.D. The only way in which this can be assured is by full process control. Other types of springs commonly shot peened are leaf springs, torsion bars, extension springs, and belleville springs.

The primary application of peening on gears to date has been to increase the fatigue strength or endurance limit in the roots of the teeth. Our experience has shown that by using the proper peening specifications under controlled conditions, an improvement of up to 20 to 25 percent in the fatigue strength of carburized or induction hardened gears can be realized. The explanation of this significant improvement is probably twofold. The magnitude of residual stress as a result of the heat treatment has been increased substantially and in addition, most gears have evidence of hob marks remaining in the tooth roots. The peening, if a high enough intensity can be achieved, will generate the high magnitude of compressive stress below the base of the tool marks.

In addition to improvement in beam fatigue strength of gear teeth, there is recent evidence that shot peening under the proper conditions can have significant effect on the retardation of pitting. More work has to be accomplished in this area but initial efforts have been very encouraging.

Another source of fatigue failures occur in shafts of various types, whether they be transmission shafts, axle shafts, PTO shafts, etc. Failures of this type will normally occur at some change in cross section of the part, whether it be a change in diameter, a keyway, spline run out, thread relief, etc. Many times these points of normal stress concentration are aggravated by a less than desirable machined finish. Again, shot peening, as a result of high magnitude residual compressive stress, along with the ability to negate the effect of machining irregularities, can increase the fatigue strength to a very significant degree.

Shot peening of many diesel engine components in the heavy equipment field has become commonplace over the past few years. Of the many engine components peened, the most common applications are those of connecting rods and crankshafts.

Most fatigue failures of connecting rods occur in the beam section of the rod, probably caused by surface irregularities on the forging. In addition, the rod forging are many times mechanically straightened, producing residual tensile stresses in the critical areas. In either case, shot peening will significantly improve the fatigue characteristics of the part either by negating the effects of the surface irregularities and/or changing the residual stress from tensile to compressive.

Occasionally, fatigue failures will originate in other areas of the connecting rod, namely the parting line face between the rod and cap or at the inner radius of the connecting rod bolt seat. In these cases, the fatigue failure is generally caused by difficulty in obtaining a good machined finish in these areas. Some manufacturers have found that it is more economical to shot peen these areas than to try to maintain proper control of the machining operations. The effect of shot peening will be to blend the machining irregularities as well as produce a residual compressive stress in the surface.

During this discussion, we have mentioned many times, the effect of shot peening in negating the effect of surface irregularities. This is particularly true in softer materials (under 40HRc). In these cases it is entirely possible that the shot peened finish will be rougher than the machined finish before shot peening. However, the direction of machining marks is almost always parallel to the direction in which fatigue cracks will initiate. The resulting shot peened finish is completely nondirectional and consequently of little significance in fatigue initiation.

The effect of shot peening of crankshafts is becoming well known. The Metal Improvement Company has had extensive experience in working with many engine manufacturers on the problem of crankshaft failures as a result of increasing the power output through turbocharging or other means. These are cases where the original engine design was adequate, but in the quest for higher output, the crankshaft design became inadequate.

The most critical area for fatigue initiation is
usually the journal bearing fillets, and less frequently, the main bearing fillets.

Many fatigue tests have been conducted to determine the increase in fatigue strength of diesel engine crankshafts as a result of shot peening the fillets. As a result of extensive testing by at least four manufacturers, the average improvement appears to be in the neighborhood of 25 to 30 percent. We have seen results as low as 20 percent and as high as 40 percent. These are the result of laboratory fatigue tests in which the stress was applied in pure bending. However, these tests are considered valid as the torsional component of stress is generally far lower than the bending component.

Special machinery has been developed for crankshaft fillet shot peening in which the fillets are peened while the bearing surfaces are shielded. The crankshaft is normally peened prior to the final lapping operation which eliminates the necessity for complete masking. The final lap or polish removes the effect of random shot impingement within the shielded area.

Induction hardening of crankshaft fillets is also becoming a common method of increasing the fatigue strength of crankshafts and does show significant improvement, because of the residual compressive stress produced by the process, as well as the relatively deep compressive case. However, as with other induction hardened parts, the results can be improved even further as a result of the higher magnitude of residual compressive stress produced by shot peening the induction hardened surface.

As a secondary process in the fillet hardening approach, the fillets must be ground, which unless properly controlled, can result in residual tensile stresses. As a safeguard after the grinding, shot peening will convert any surface tensile stress to compressive.

Many engine manufacturers are currently investigating the concept of shot peening crankshafts in connection with the rebuilding process. Many crankshafts are reground during the rebuilding process, and during the regrinding, both the bearing surfaces and fillets are ground.

If the original manufacture of the crankshaft included fillet improvement such as induction hardening, rolling, or shot peening, some or all of the effect of the fillet improvement will be removed by the grinding. In addition, if the grinding is not properly controlled, the fillet surfaces could contain residual tensile stresses. Consequently, use of the shot peening process after regrinding would tend to restore most or all of the residual compressive stress from the original manufacturing process, and compensate for any residual tensile stress developed during the grinding operation.

Another major application of shot peening in engine manufacture is that of valve springs. Most if not all engine manufacturers have valve springs shot peened as a matter of course to derive the benefits mentioned in the earlier discussion of springs.

Other engine components which have been shot peened on a production basis are piston pins, pistons, piston rings, camshafts, and timing gears.

Much of the discussion thus far has dealt with the benefits to be derived through the introduction of surface residual compressive stress to various types of mechanical parts by means of the shot peening process. To maximize these results it is necessary to select the optimum set of shot peening specifications for a particular part and then to exercise complete control of the peening process.

Too often, shot peening will be used successfully on a particular part, and when it is decided to apply shot peening to another part, the same set of specifications will be used without sufficient regard for differences in part geometry, hardness, duty cycle, etc. The proper selection of shot peening specifications can greatly affect the degree of improvement to be realized.

Some of the main factors to consider are the following:

1. Minimum Fillet Radius - May limit the shot size to be used.
2. Minimum Cross Section - May limit shot peening intensity to avoid distortion.
3. Surface Finish - If rough, must select shot size and intensity sufficient to generate deep enough layer of residual compressive stress.
4. Hardness - Any part harder than 50Rc requires the use of
special hard shot for optimum results.

On some parts there may be more than one fatigue critical area and these areas may require different peening specifications to optimize the results in each area. In these cases, it is often wise to perform multiple processing, each with a different set of peening specifications.

Once the specifications have been determined, the control of the process then becomes critical. All shot peening operations should be performed automatically except in those rare cases where certain areas are inaccessible to automatic means of processing. Manual peening cannot be relied upon to produce a uniform layer of compressive stress nor will it produce uniform results repeatedly over a number of parts. Consequently, any machine in which shot peening is performed should have the capability of rotating or translating the part under the shot stream during a timed peening cycle.

Assuming the part is to be peened automatically, there are then three basic areas of control; these being, peening intensity, coverage, and control of the media.

Intensity control is important as the depth of the compressive layer is a function of the peening intensity. Intensity is determined by use of the Almen strip. This is a 3/4 inch by 3 inch strip of 1070 spring steel with a hardness of 44-50 Rc. There are three different strips of varying thickness for use in different intensity ranges. Before it is exposed to the peening operation, the strip is flat within ±.001. While restrained flat on a steel block, the strip is positioned in the same plane as the critical area to be peened, and then exposed to the shot stream at a velocity which has been predetermined either by adjusting air pressure or wheel speed, depending upon the type of equipment being used. Upon removal from the block, the Almen strip will no longer be flat, but will have a curvature which is convex on the peened side. The higher the peening intensity, the greater will be the arc height. The measurement of the arc height is a measure of the intensity. If the arc height is not within the specified limits of intensity, the shot velocity must be increased or decreased accordingly and additional intensity determinations made until the specifications are met. Additional intensity determinations must be made at longer periods of exposure to ascertain that longer exposure will not significantly increase intensity.

Many times, it will be necessary to expose the part for a longer period than the Almen strip to assure full coverage of the part.

Next it is necessary to determine the actual exposure time to determine complete peening coverage of the part. Full obliteration of the surface is necessary to achieve optimum results. The determination of full coverage has historically been accomplished by visual inspection with a 10X glass. This is adequate with a well trained inspector. However, the Metal Improvement Company has recently developed a more sophisticated and certain method of coverage determination. It is designated as the "Peenscan" process. In this process the critical area is coated with a fluorescent tracer dye which has been formulated such that it will only be removed with full surface obliteration by the peening shot. A quick inspection under a black light will readily indicate whether the peening coverage is complete.

The final aspect of process control is that of the peening media. Conventional peening media is cast steel material which is basically spherical in shape. After repeated impacting against the surface of the parts being processed, the particles fracture, flatten, or otherwise lose their spherical shape. Those that fracture or otherwise are severely deformed tend to become abrasive and can produce sharp indentations compared to the desirable smooth, rounded, indentations caused by spherical shot. In addition, as particles fracture to a high degree, the intensity deteriorates because of the smaller particles. This problem is compounded with the use of special hard shot because the harder shot has a much higher fracture rate. Frequent inspection of the shot in the machine is required to assure a minimum of unacceptable media. The fragmented shot may be separated by means of equipment designed for this purpose.

For further reference regarding the control of the shot peening process we recommend MIL S 13169.

In summation, the high magnitude surface residual compressive stress produced by the shot peening process is effective in extending the fatigue life of virtually any mechanical part, and the secret to achieving maximum improvement is the selection of the best shot peening specification, followed by exacting process control.