Shot Peening – A Viable Method to Extending Component Life

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ABSTRACT

Engineers are constantly looking for better tools which can be used to design extended life into various components of heavy duty equipment. One of these tools is the shot peening process and our purpose here is to bring an understanding of this process and how we can apply it to a variety of applications. Shot peening, with its resultant residual compressive stresses, has shown itself to be a viable low-cost alternative to meet higher capacity requirements within the same design envelope. We will look at some varied applications including Austempered Ductile Iron, as well as some of the process specification parameters. We shall also look at the controls required to give consistent levels of coverage and intensity along with a view to the latest state-of-the-art microprocessor equipment in use to assure the highest levels of quality control.

THE ENGINEER'S QUEST for improved component life normally requires more than just arriving at a prolonged fatigue life figure. It also requires providing sufficient torque capacity, weight, size, quality, producibility and cost, all to be within prescribed parameters. The process of controlled shot peening can be an effective tool in the original design to fulfill those requirements. When properly processed, shot peened gears allow for increased operating stress levels. This allows the use of higher strength materials which in the past have not been considered for these applications due to their notch sensitivity. This process has been used for many years on gears and springs, however, the past several years have shown a great increase in the number of applications. This has resulted primarily from the demand for improved reliability by the manufacturer and improved process controls by the shot peening industry.

We must also keep in mind that many manufacturing processes leave residual tensile stresses at the surface which are further adversely affected by changes in cross-section and tool marks. Depending on how the part had been processed, substantial levels can be reached. Readings as high as 80 KSI tensile have been measured after grinding.

Before we can look at specific applications we must first understand the shot-peening process and how it beneficially affects fatigue life. If we look at fatigue in general, we know that: 1) Cracks nucleate at the surface as a result of tensile stress (residual and/or applied). 2) Propagation follows as the load continues to act. 3) Fracture occurs when propagation has progressed to the point where there is no longer sufficient area to support the load. 4) A crack will not nucleate or propagate through a zone of compressive stress. By using this information we can see that if we can keep the surface of the part in compression we can inhibit the formation of a fatigue crack and thereby extend useful life.

Shot peening allows us to do that. It is defined as the bombardment of a surface with spherical media to produce a layer of high magnitude, residual compressive stress, as shown in Fig. 1.

How Peening Improves the Surface Layer

Fig. 1 (1*)

*Numbers in parentheses designate References at end of paper.
The depth of compressive stress is purely a function of kinetic energy transfer. In steel, this induced compressive layer will be approximately equal to the dimple diameter, providing the impingement angle is near the normal 90°. If we peen so that the dimples overlap we will induce this depth of compressively stressed layer over the exposed surface. If we vary this angle we will affect the compressive layer depth as can be seen in Fig. 2. In this figure depth is expressed in Almen units, a measure of intensity.

Fig. 2

In looking at the cross-section, after peening, and plotting a measure of the stress distribution we will see a curve similar to that shown in Fig. 3.

Fig. 3

As we can see, the magnitude of the compressive stress is maximized at, or slightly below the surface, and will measure approximately 60% of the tensile strength of the material. This will vary with a somewhat lower percentage for higher strength material, and somewhat higher percentage for lower strength. The depth of compression (intensity) will also vary in the same manner; that is, the higher the strength, the less the depth. It should be added here that these figures are for steel, unless otherwise indicated, and are illustrated in Figs. 4 and 5. The X-ray diffraction method was used to measure surface and sub-surface stresses.

Fig. 4

Unlike most other processes, there is no non-destructive test currently available to verify that parts have been shot peened properly. That is to say that all pieces in a given lot have had the proper depth and magnitude of compressive stress produced over the desired surface. Therefore, positive control of all four phases of the process is essential to ensure repeatability. We will look at each one individually.

1) Shot integrity - This is the first area which should always be addressed. To maintain the mass in the kinetic energy relationship we must inspect the shot at regular intervals to prevent it from deteriorating into unacceptable shapes and sizes, the limits of which are specified in Mil-S-13165B. To do this with cast steel
shot we use a series of vibratory screens and a shot classifier. After passing through the screens the shot is separated by size, but not necessarily with an acceptable shape. It is then directed to the inner spiral of a vertical, two-spiral mechanism. As the shot disperses and begins to accelerate down the spiral, the round shot will gain sufficient velocity to exit and be caught by the outer spiral. The misshapen and broken shot simply tumbles and slides, remaining in the inner spiral. When the classifier is attached directly to the machine, the acceptable shot is directed back to the machine for reuse and the broken shot is directed to the scrap container.

2) Intensity - As mentioned earlier, this is a measure of the compressive layer depth and gauged by the use of Almen strips. The specifications of the strips are defined in Mil-S-13165B specification and are available in three (3) thicknesses (Fig. 6). Selection is dependent on the desired intensity range required.

These strips are used to calibrate the peening equipment. For each calibration test, Almen strips are individually attached to a test block and exposed to the shot stream (Fig. 7) in the same manner that is called for on that particular part for the specified period of time. When the strip is removed from the block it will curve upwards; peened side goes convex. It is then placed in an Almen gauge where the arc height is measured (Fig. 8). If, after peening the strip per the process specification, the arc height is within the prescribed limits, we know we have an acceptable set-up.
3) Saturation - This is the term used to describe the time required to fully shot peen a part, under certain conditions, in order to attain a specific intensity, with a particular shot size, in a minimum amount of time. In order to achieve this end we must establish a saturation and determine this point. By definition the saturation point is achieved at the time $T$ where extending the exposure time to $2T$ results in an increase in arc height of less than 10% between these two points. To accomplish this we vary the parameters, set up an Almen strip and block, expose it to the shot stream for a period of time, measure and plot the arc height, then repeat it several times, extending the exposure time until we have developed a curve similar to that shown in Fig. 9. When we have achieved this we have determined the intensity curve for those conditions.

4) Coverage - This final control assures us that we have complete dimpling or obliteration of the surface as shown in Fig. 10.
If there is incomplete coverage, the unpeened areas will have tensile stresses surrounded by compressively stressed areas which could result in premature failure. As the surface hardness increases so does the difficulty of being able to detect it with the naked eye. (Recall our earlier discussion on the relationship between surface hardness, dimple diameter and depth of compressive layer). Two acceptable methods have been developed to determine this coverage per the Mil-spec. They are: a) Visual examination with the use of a 10X magnifying glass; b) Dyscan tracer liquid used in the Peenscan process.

Visual examination with a 10X glass is self-explanatory. It becomes a problem with hardened parts, say carburized gears in the range of 58-62 R/C. The dimpling is difficult to discern and can be very subjective. Differ-ences of opinion are not uncommon.

The dyscan tracer liquid is another matter. It is accomplished by coating the part, allowing it to dry, then placing it in the shot stream and running it according to the production process. Upon completion of the normal cycle, the part is placed under an ultraviolet light in a darkened area. If the part was properly peened, all of the tracer liquid would have been removed and there would be no "glow." Improper peening coverage would immediately be evident in those areas. A very objective method of determining coverage.

There seems to be some confusion when discussing intensity, saturation and coverage in that sometimes the terms are used interchangeably, especially saturation and coverage. Intensity is simply a measure of the arc height of an Almen strip after it has been exposed to the shot stream. It can be measured at any point in the cycle. For example, when developing the saturation curve we plot several intensity readings to determine saturation, none of which are the "correct" reading. These are measures of the kinetic energy transferred to that point in time. Saturation occurs when the amount of energy being transferred is no longer generating a layer of compressive stress, but rather stretching the exposed surface. This point is the bend or "knee" in the curve at time T and it is essentially a summation of energy that we imparted during the incremental development of that curve. Once established, this curve becomes the intensity curve used to calibrate the machine. If there is an excessive amount of mixed or broken shot, we will affect the amount of energy transferred which could yield an out-of-specification arc height reading as shown in Fig. 11.

Over the years, the shot peening industry has made great strides in process control through use of micro-processors. One of the first was a piece of NC equipment, Fig. 12, used to peen the center wing box section of the Grumman F-14. The part measures about 5' wide, 1-1/2' deep and over 20' long, and is made of 6-4 Titanium alloy. Its function is to connect the pivoting wing assemblies to the fuselage and requires more than 100 electron beam welds in the final assembly. The purpose of the peening is to negate the potential detrimental effects of tensile stresses in the heat-affected zones. Since the top and bottom sections are
relatively thin, both sides must be peened which poses no particular problem in doing the outside. The inside requirements were much more complex because the nozzle, an internal deflector type, had to be positioned precisely in the X, Y and Z planes to assure that each of the welds was properly peened in repeatable fashion, piece-to-piece and lot-to-lot.

Micro-processor controlled equipment is now available that will monitor the process variables throughout the peening cycle and transfer instantaneous readings of these to hard disc storage at prescribed intervals. If any of the variables should drift outside the limits programmed, the cycle will abort automatically, remember the exact point shut-down
occurred, document the shut-down in the hard
disc record for printout and explain the cause
of the abort to the operator on his CRT. The
machine will not restart until the cause has
been corrected, at which time it will pick up
the process at the point which it left off and
continue till cycle is completed.

This micro-processor controlled equipment,
with continuous monitoring capabilities, has all
but eliminated the possibility of shot peening
a part improperly.

APPLICATIONS

As mentioned earlier, more and more types
of component parts are now being shot peened.
Probably the most widely shot peened parts are
springs of all types, shapes and sizes. Con-
necting rods, in most all diesel engine designs,
call for shot peening because of the cost
effectiveness of the benefits realized. Another
engine part widely peened is the crankshaft.
Here we peen the radii adjacent to the journal
and bearing diameters. Steering and suspension
parts have also been likely candidates.
Various steering arms and linkages are currently
being peened as are I-beams in heavy-duty
vehicle applications.

Peening procedures were developed in con-
junction with component manufacturers on two
separate applications. The first was a torsion
bar that connects the steering shaft to the
gear box. The objective was for 500,000 cycles
within the current design constraints which was
only capable of 200,000 cycles. Shot peening
increased the life to a point beyond 600,000
cycles with no other changes required in
material, heat treatment or processing. A
second application is in a clutch release
mechanism clevis pin. The part was failing at
the radius where a change in section occurs, in
what would translate to about three months of
service. After peening, testing of the samples
was terminated as no failures had occurred at
2,000,000 cycles: an increase of over 11 times
the life. Again, nothing else was changed
metallurgically and a redesign of the part
could have necessitated a redesign in the entire
release system.

An area with a great deal of current
interest is the use of cast austempered ductile
iron (ADI) material in the manufacture of gears
and other components. The vehicular industry
is finding more and more applications where
properly processed ADI is supplanting forged
steel gears. As we know, the term ADI refers
to a variety of materials whose properties can
be varied to yield a wide range of properties.
The objective is a quality component part at a
lower cost. By using a cast design the gear
blank can more closely assume the shape of the
finished part. This results in lower manu-
facturing costs because of less metal removal
and tool replacement. The cost of material is
also lower.

As can be seen in Figs. 13 and 14, shot
peening has a very beneficial effect on ADI
material by significantly increasing the
fatigue stress levels. It has also been estab-
lished that ADI has a resistance to both
abrasive and adhesive wear, which is nearly
twice that of steel of equal hardness.
The shot-peening industry has come a long way in providing a service that can be an invaluable aid to the designer in holding the line or reducing the cost of components. It also is in position to provide parts with certified quality levels to assure the consistency of one part to the next. Consider how some view the reliability of controlled shot peening:

1) The FAA recently certified an upgrade in gas turbine engine life from 12,000 start/stop cycles to 20,000 based on the improved shot peening controls.

2) Lloyd's Register of Shipping has certified that controlled shot peening will increase fatigue stress levels 20% on case hardened carburized gears (6).

REFERENCES