ABSTRACT

Evaluating dynamic loads in gear design has always been a major design consideration. In addition to stresses due to applied loads, however, the impact of residual stresses must also be considered. Shot peening as described in this paper produces beneficial residual compressive stresses under strictly controlled conditions. Compressive stress prevents or limits failure in gearing due to fatigue failures at the fillet, pitting failure at the pitch line, as well as providing other benefits for gear designers and users.

IMPROVED GEAR LIFE THROUGH CONTROLLED SHOT PEENING

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The search for greater gear life also involves improvement in cost, weight and increased power output. There are many events that affect gear life and this paper addresses those relating to fatigue, gear tooth pitting, fatigue strength losses due to the heat treating processes and shot peening technique. The capability of shot peening to increase fatigue strength, increase surface fatigue life, eliminate machine marks which cause stress risers, and to aid in lubrication, when properly controlled, suggests increased use and acceptance of the process.

Fatigue failures usually occur as follows: The first phase is the initiation of a crack at the surface that contains either residual tensile stresses (caused by manufacturing procedures), or applied tensile stresses (external stresses caused by gear tooth loading). This is followed by crack propagation through the part as at the root of a gear tooth where tensile loads are greatest. In time, catastrophic failure occurs as the cross section of the part is no longer capable of carrying the applied load.

Shot peening benefits derive basically from the fact that a crack will not initiate in, or propagate through, a compressively stressed layer.

When spherical media of controlled size and shape strike the surface at an angle of impingement approaching normal, a compressive layer is induced which will be in depth in steel about equal to diameter of the dimple, and about twice the diameter.

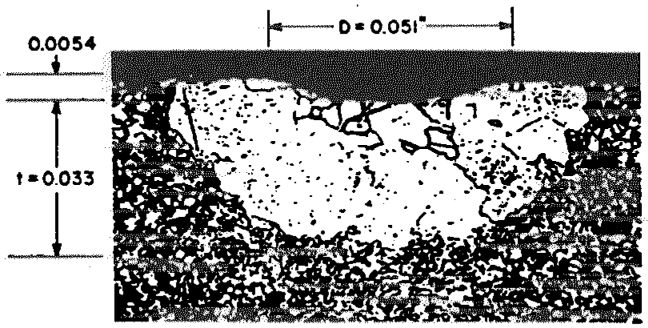


Fig. 1, Ref. 1*

In Fig. 1 we see the effect of shot which impacts the part at an impingement angle of 90 degrees. As angles of impingement vary from ninety degrees to forty-five and smaller, the depth of compressive stress induced in the same material by shot of equal size, mass and hardness impelled at the same velocity will induce stresses of increasingly shallower depth, as shown in Fig. 2.

Angle of impingement is but one of the variables that deserves as close control as possible and is covered in more detail later in this paper under equipment control and automation.

*Designates references at end of paper.

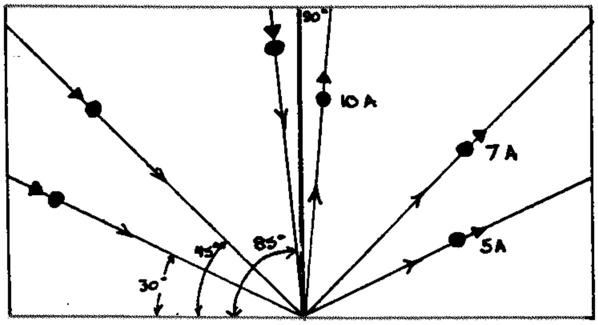


Fig. 2
Almen intensities measured in Almen units - intensity being a function of size, mass, hardness and velocity. Note the intensity varies as the size of the angle of impingement.

If the part is peened by a great number of shot (under controlled conditions) so that the edges of the dimples caused by these shots all touch or overlap, a consistent uniform layer of compressive stress is caused to be formed.

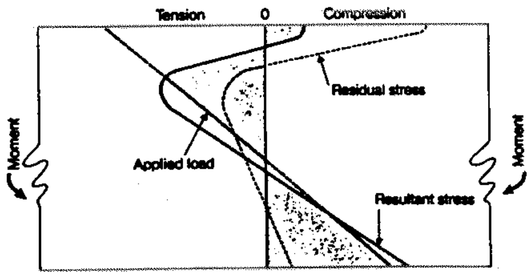
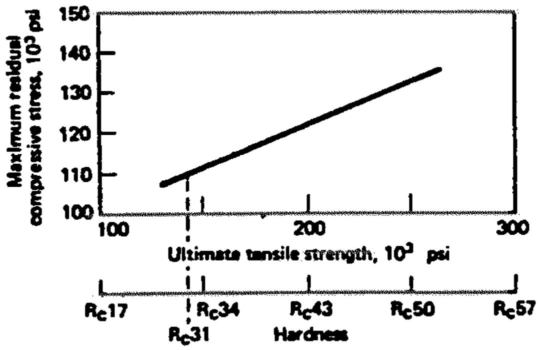


Fig. 3, Ref. 4

This sketch shows qualitatively the distribution of stress in a beam which has been shot peened on the upper surface. The broken residual stress line shows the beam in equilibrium with no external forces, the area under the stress distribution curve in the regions of compressive stress must be equal to the corresponding area under the curve in the region of tensile stress. The sum of the moments of these areas must be equal to zero.

The solid line shows the resultant stress after a bending moment is applied. This resultant stress will be equal to the algebraic sum of the residual stress, after shot peening and the stress due to the applied load at that depth.

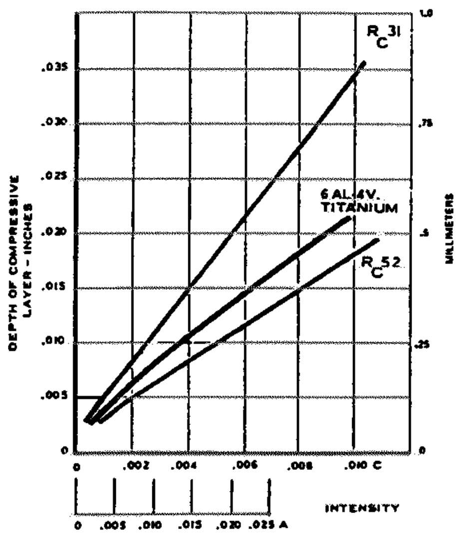
Note especially that after loading, shown by the intermittant broken line, that the peened surface still retains a compressive stress. This stress will inhibit formation of surface cracks and takes advantage of the fact that a crack will not propagate into a compressively stressed layer. The magnitude of the residual compressive stress shown at or just slightly below the surface of the peened member will be approximately 50 to 60 percent of the ultimate tensile strength of the base material. See Figure 4.



Ultimate tensile strength and surface hardness determine the residual stresses after peening.

Fig. 4, Ref. 7

Since the amount of energy imparted to the shot peened surface is a function of the mass, velocity and hardness of the shot, the hardness of the material being peened will also determine the depth of compressive stress. The variables are in addition to the aforementioned angle of impingement.



DEPTH OF COMPRESSIVE STRESS VS ALMEN INTENSITY FOR STEEL & TITANIUM

Fig. 5, Ref. 4

The standard for measuring energy applied to the work piece is the Almen strip. A good description of the detail of this method of specifying intensity can be found in the Mil Spec 13165B Amendment II, Ref. 3. Note in Fig. 5 that as the hardness of the work piece increases the depth of compressive layer decreases --- presuming the factors of shot size, mass, velocity, hardness and angle of impingement remain constant. Control of the depth of compressive stress is very important because the designer or user of shot peening must take other factors into consideration when selecting the intensity. These are wear, general erosion if any, possibility of F.O.D. (foreign object damage), surface finish requirements, an acceptable level of compensating tensile stress, etc. On very thin parts, depth of compressive stress can be a very important matter since, as a general rule, the depth of compression should not exceed ten percent of the thickness of material per side in order to keep tensile core stresses to an acceptable maximum.

Finally, as we see in Fig. 4, it is extremely important to be sure that the design load is such that tensile stresses resulting from that load are kept below the level of the residual compressive stresses which are a function of the ultimate tensile strength of the material being peened and generally are in the range of 50 to 60 percent of the UTS (ultimate tensile strength) of the base material. A tensile load level maximum is generally accepted to be 40 to 50 percent of the UTS of the material being peened.

The main effects of controlled shot peening on gears are as follows:

1.) Improved fatigue strength of the gear tooth in the root fillet.

2.) Increased surface fatigue life to reduce pitting and increase durability.

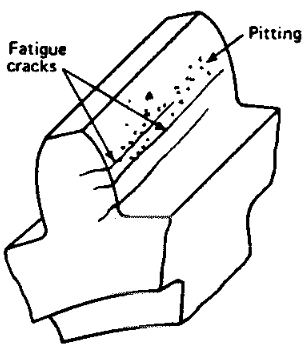
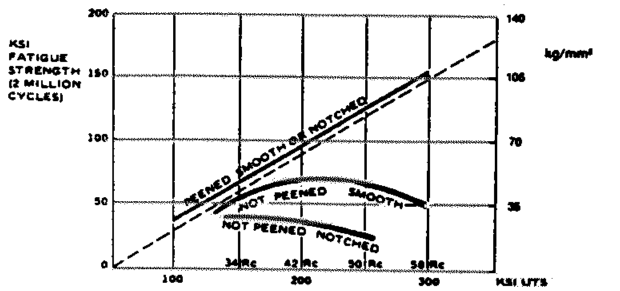


Fig. 6, Ref. 7
Typical pits and fatigue cracks

Other benefits accruing from shot peening gears are aiding in lubrication of the gear by virtue of the many small reservoirs (dimples) that can store lubricant at the point where it is most needed - negating the squeegee effect of rolling sliding contact of two very smooth surfaces. Of course, other considerations must be met to determine the amount of dimpling that can be tolerated or obtained.

Another benefit is the elimination of continuous machine lines on the gear tooth flank by peening in the "green" state.

Typically, a gear's surface hardness is increased to allow it to carry higher loads by heat treating. Hardening by carburizing, nitriding and other hardening processes can cause dimensional changes which may require remachining. Note too, that on through hardened gears, as tooth hardness increases above 43 RC (about 200,000 psi) fatigue strength actually decreases. See Fig. 7.



COMPARISON OF PEENED AND UNPEENED FATIGUE LIMITS FOR SMOOTH AND NOTCHED SPECIMENS AS A FUNCTION OF ULTIMATE TENSILE STRENGTH OF STEEL

Fig. 7

As hardness increases, the reduction in fatigue strength in unpeened steel specimens, both notched and unnotched, occurs at about 45 Rc. This drop in fatigue life is believed to be due to increased notch sensitivity and brittleness. With peening the strength level can be raised by using higher hardness, a practice regularly used by the aircraft industry. It must be remembered that when peening hardened gears, or any other hardened material, it is extremely important that the peening media be at least as hard as the part being peened. This is necessary to generate maximum compressive stress in the gear by shot peening. A significant decrease in fatigue strength will be noted if the hardness of the peening media does not at least equal the hardness of the part or specimen being peened.

In addition, it is important to recognize and to take into account the residual tensile stresses induced on the gear tooth profile and root during grinding. These tensile stresses can be overcome by shot peening to induce beneficial compressive stresses.

If the roughness of the tooth flanks produced by the shot peening is objectionable, the flanks may be shaved (rather than masked before peening); however, control of surface temperatures during lapping and honing operations is important.

The greatest increases in gear life, when comparing peened versus non-peened, are found in through hardened gearing. Shot peening of through hardened pinions can yield as much as thirty percent improvement in fatigue limit. A thirty-three percent increase on induction hardened 4140 material is reported. The same authors also claim that nitrided steel surface tests showed moderate results. Seabrook & Dudley - Ref. 8.

Today, gears are frequently shot peened after carburizing. Figure 8 below shows how shot peening can stretch fatigue life of carburized gears or to make it possible to use smaller transmissions for larger loads. Increases of 15-40 percent are commonly found.

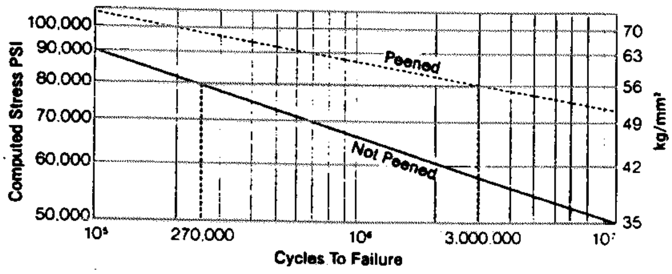
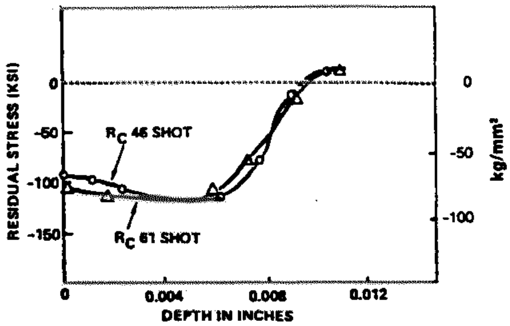


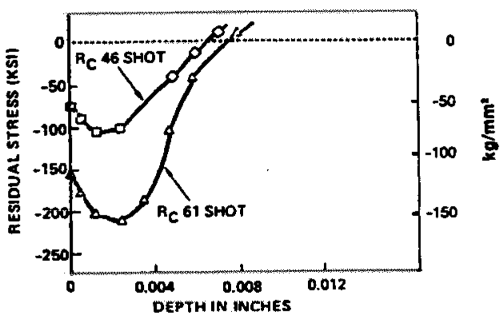
Fig. 8, Ref. 4

Of course, proper selection of shot size and hardness are important considerations. Special hardness (55-65 Rc) shot is recommended for case-hardened carburized gears in order to give a higher magnitude of compressive stress. See Figs. 9, 10, 11 below.



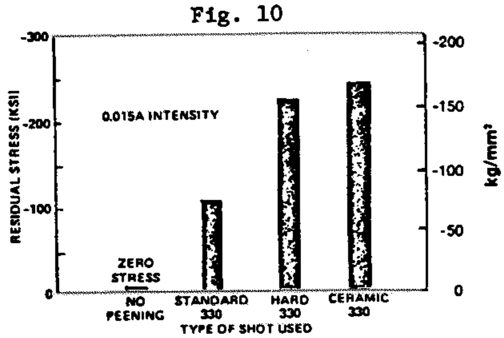
PEENING 1045 STEEL AT Rc 48
WITH 330 SHOT

Fig. 9



PEENING 1045 STEEL AT Rc 62
WITH 330 SHOT

Fig. 10



RESIDUAL STRESSES INDUCED
ON 300M USING VARIOUS SHOT

Fig. 11

Townesend and Zaretsky stated that it is well known that shot peening produces residual sub-surface stresses in steel in addition to the residual stresses produced by case carburizing, hardening and grinding. They theorized that the additional residual stresses induced by shot peening should account for the increased life of carburized and hardened A151 Spur Gears. Subsequent tests showed an increase of 40 percent for the shot peened gears over the standard gears at a depth of maximum shear stress in addition to a 350 percent increase at a depth of 0.5 mil. Further, there was an increase in surface pitting fatigue of 1.6 times that of not shot peened gears. See Ref. 9.

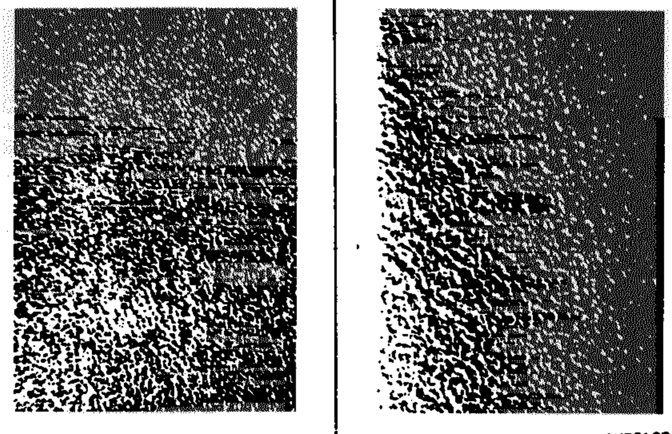
As a result of the growth in confidence in the shot peening process, Lloyd's Register of Shipping, Ref. 10, allows an increase of tooth loading for both wear and strength up to 20 percent for controlled shot peened gears.

The term "controlled" is extremely important and leads us to a discussion of shot peening controls and the changes that are now taking place that allow the peener to accurately meet the requirements set forth by the design engineers. With controlled conditions of shot peening, the designers can establish specifications that they have confidence will be met by their shot peening service. There is still no non-destructive method of inspection, other than for coverage (Peenscan*). This problem has been largely alleviated through the use of microprocessor controlled shot peening equipment.

As covered previously, we have the Almen strip to measure intensity for a given set of conditions of shot size, shot velocity, shot hardness and angle of impingement. (Ref. 3) From that same reference, we have specifications for the shot itself, steel and glass, which covers screening tolerances of new shot by size, sets limits on hardness where applicable, specifies uniformity of shot in the machine and standards for shape with allowable deviations thereof. Shot quality is important to successful peening and must be continuously monitored. You must be especially vigilant in regard to those machine installations where a single size shot is run continuously. The temptations to add make up shot whenever reduced flow is noted without checking, screening and sizing the old shot seems to be irrisistable to production people. Inevitably, quality of peening becomes degraded as the shot breaks down into odd sizes and increasing numbers of broken particles. Concurrently, those expected improvements in fatigue life will showly and quietly degrade as well.

The third item to consider is coverage. Since the discovery of shot peening in the late 20's, the 10X magnifying glass has been the recommended tool for checking coverage. Specifications generally require full or complete (100%) coverage. Others call for 125%, feeling that the additional insurance of 25% will guarantee the 100% coverage actually required for good peening. The uncertainties of measuring or checking coverage had

PARTIAL COVERAGE | **FULL COVERAGE**



PART OF ORIGINAL SURFACE VISABLE BETWEEN DIMPLES. DIMPLES NOT OVERLAPPING.

COMPLETE DIMPLING OF ORIGINAL SURFACE. ORIGINAL SURFACE COMPLETELY OBLITERATED BY OVERLAPPING DIMPLES.

Fig. 12

become so great that one of the largest aircraft manufacturers in the United States has specified 200% coverage on certain critical parts in the hope that they will get at least 100% coverage on all of the part during manufacture; a sad commentary on the 10X glass as an inspection tool. The borescope, while allowing examination of cavities and holes, suffers from the same limitations of limited field and mobility in contoured areas.

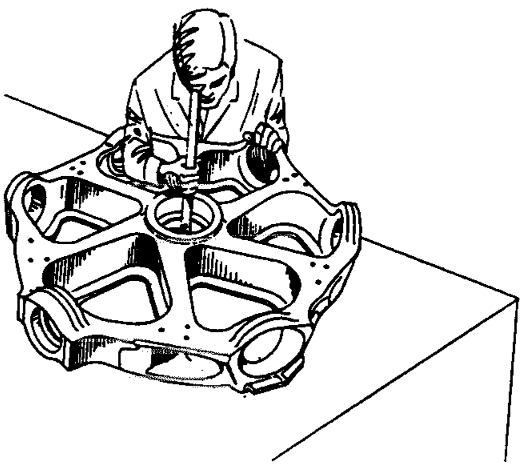


Fig. 12a

The obvious limitations of the 10X glass are its small field, making total inspection of large parts a physical impossibility along the short focal length, and often does not permit inspection for coverage of critical clevises, roots, radii and holes where there is not sufficient room to get the glass close enough to focus on the peened surface. On very hard parts, Rc 55 and above, it is often difficult to determine whether the part has been covered, and many times shot peeners have been required by customers' inspectors to peen very hard parts from 500%-600% coverage - simply to assure these inspectors that the coverage is complete.

There now is a process for measuring coverage that does away with the problems of the glass. This process (Peenscan) uses a non-elastic ultra violet (UV) sensitive compound that is painted or sprayed on the part prior to peening and during the set up operation. When the coated part is peened, this material (Dyescan) comes under direct impingement and will be removed only in those areas which have been struck at reasonable angles of impingement. Removal of the UV material is gradual and is completed when the part is totally covered by shot peening. When inspected with a UV light, if there are any areas improperly peened there will be evidence of some material remaining as a white shadow of varying intensity, depending upon the degree of coverage actually obtained. (See Fig. 13).

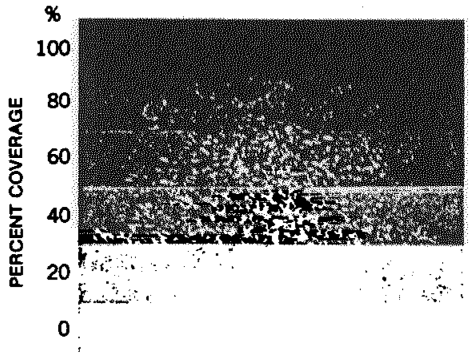


Fig. 13, Ref. 4

Six coupons peened to amount of coverage shown. Note variation of color under UV light from full fluorescence at 0% coverage to complete black, which denotes full coverage.

This process is outlined in the Mil Spec 13165B - Ref. 3, and has been accepted by the entire defense agency.

The Peenscan process is used to set up automatic equipment and as a control in production on a statistical sampling basis.

Having assured ourselves of the questions of intensity and coverage, we now come to the most recent developments in controlling the shot peening process. Though it has been said that the industry has had automatic equipment for a number of years, the shot peening operators have never satisfied most gear manufacturers on the ability to control the process completely and accurately. Therefore, the improvements in fatigue life produced by peening have never been assigned values for the gear designer to use in designing gears. Thus, the benefits of shot peening have largely been used as "insurance policies" or as "band-aids" to cover mistakes made in manufacture and design, or to allow increased loads to be put on gearing already designed and in production.

The advent of microprocessor controlled shot peening machinery is causing a change in this philosophy. The concept of total control of the shot peening process has been successfully developed and many of these machines are in service today. Once a successful shot peening process has been developed, and the process variables determined, this process can be precisely duplicated time after time. This requires that all of the process variables be constantly monitored with high and low limits set on each. The variables normally monitored are shot flow, air pressure (or wheel speed), turntable or roller speed, and nozzle oscillation. If desirable, the nozzles can be programmed to vary their rate of travel across the part, or turn on or off at prescribed intervals during the cycle. If any of the variables wander outside of the preset limits, the peening cycle is caused to abort at that point with a print-out made of the malfunction. At the end of each peening cycle, a print-out is made of each of the process variables. This information can also be stored on floppy discs for ease of physical storage.

With the advent of this latest state-of-the-art equipment, it is now time for the gear and transmission industry to establish values for controlled shot peening. This step would put shot peening in a new perspective as a tool for designers to be used in manufacturing quality gearing.

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