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Shot Peening and its Effect on Gearing

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ABSTRACT

With the trend in gear transmission towards higher capacities, smaller size and overall increases in strength, shot peening is a viable and low-cost alternative to major redesign or increased material costs due to part-size increases. Understanding shot peening can be an effective means to a solution for these new design challenges that can only be made by having an understanding of this tool's capabilities. The ability to increase fatigue strength, increase surface fatigue life, eliminate continuous machine marks which produce stress risers in the tooth flank, and aid in lubrication are key factors in aiding gear designers.

THE PURPOSE OF THIS PAPER is to provide gear design engineers with an understanding of how to use shot peening as an important tool in reducing costs in gear system design, as well as knowing when that tool should or should not be used. Shot peening is effective in combatting problems related to fatigue, gear tooth pitting, and fatigue strength losses due to various heat-treating techniques.

Though designers of marine gearing and turbine propulsion systems have long been aware of shot peening as an effective tool in combatting fatigue, new designs for agricultural machinery, speed reducers and gear motors are incorporating the process into the initial design **stages.**

DISCUSSION REGARDING FATIGUE

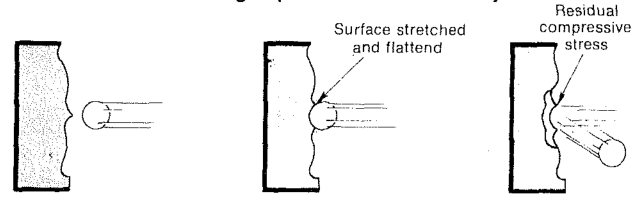
To understand why shot peening is an effective tool in fatigue-related problems, it is necessary to understand the theory surrounding shot peening. It is known that fatigue failures consist of three events: A) The initiation of the crack at a surface that has either residual tensile stresses (possibly produced by assorted machining operations) or applied tensile stresses (as in external forces produced by gear tooth loading). B) Followed by crack propogation or movement through a member (as in a gear tooth). C) Followed by eventual fracture of the member due to insufficient cross-section of the member making it unable to carry the applied loads.

Based on crack propogation theory, a crack will not propogate into a layer that has compressive stress.

SHOT PEENING AND ITS EFFECT ON FATIGUE

By utilizing this principle, shot peening is defined as the bombardment of a surface with small spherical media (the shot) to produce a thin layer of high magnitude, residual compressive stress, as shown in Fig. 1.

How Peening Improves the Surface Layer



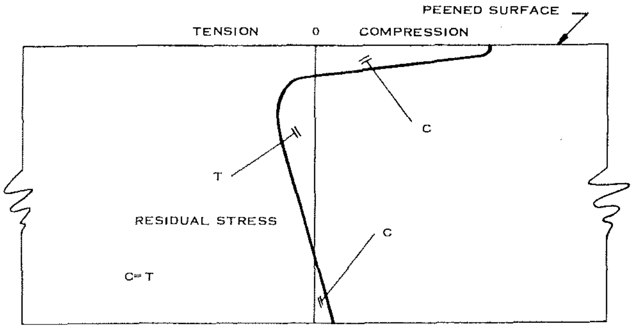
As shot particles strike a part, they deform the surface grains plastically, stretch the surface radially, and induce a tensile stress. When the particles bounce off, tensile stress is relieved, and a residual compressive stress is left in the surface layer. This stress resists pit formation and offsets the effects of the applied load.

Fig. 1 (1)*

*Numbers in parentheses designate References at end of paper.

By eliminating event B of fatigue failure, the fatigue crack can be arrested.

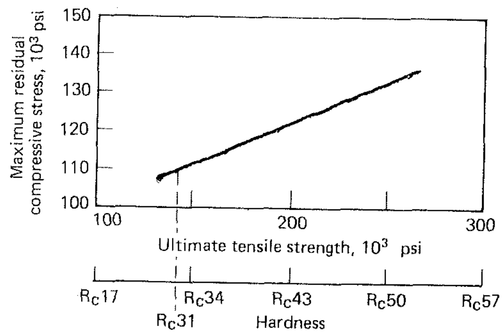
The stress distribution through the cross-section of a part can be shown as in Fig. 2.



DISTRIBUTION OF STRESS IN A SHOT-PEENED BEAM WITH NO EXTERNAL LOAD

Fig. 2 (2)

A zero point is randomly selected, and increasing compressive stresses are shown by movement from left to right from the vertical datum point, and increasing tensile stresses can be shown by moving from the datum point from right to left, then the stress distribution through the member can be graphically shown if the peened surface is at the top of the member. The greatest magnitude of the compressive stress will occur at the top of the peened member, or just slightly below the surface, and will be approximately 50 to 60 per cent of the ultimate tensile strength of the base material (See Fig. 3).



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

Fig. 3 (3)

The depth of the compressive stress is totally a function of the kinetic energy imparted to the peened surface and is a function of the mass of the shot times the velocity. This depth of compression, or the point at which compressive stresses change to tensile stresses (referred to as core tensile), is also a function of the hardness of the material (See Fig. 4).

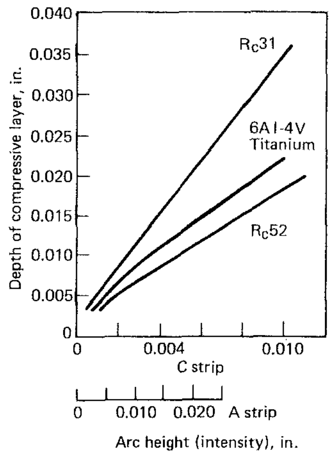


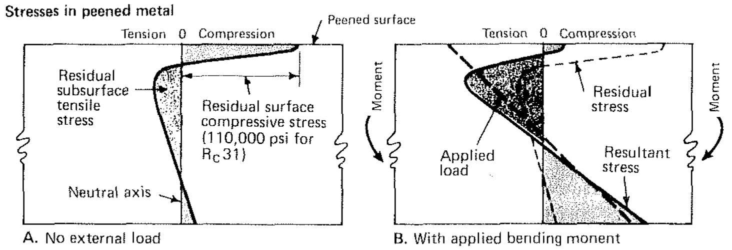
Fig. 4 (3)

This kinetic energy is measured by a standard known as an "Almen" strip. A more complete description of how this works will be described later, but for now, as shown in Fig. 4, the intensity with which a part is being peened is increasing as we move from left to right.

At a given intensity (the measurement of the kinetic energy) the depth of compression is deeper on a softer material than on a harder material. This depth of compression is critical because it cannot exceed ten per cent of the thickness of material per side.

When a part that has been peened has an external load applied to it, the off-setting tensile stress produced by the load will decrease the magnitude of the compressive stress introduced by the peening. This compressive stress will be retained if the part is loaded no more than 40 to 50 per cent of the ultimate tensile strength of the material or below the elastic limit or yield point.

As shown in Fig. 5A, for a material with a hardness of R_c31, the part has the stress distribution shown without an external load. Upon application of the load, the curve will shift as shown in Fig. 5B.



Peening continues to protect the surface from fatigue as long as tensile stresses from applied load are less than residual stresses.

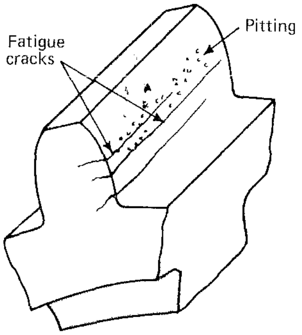
Fig. 5 (3)

SHOT PEENING'S IMPACT ON GEARING

By understanding the effect produced by peening, we can now determine the ways in which it can be beneficial to the gear designer. Shot peening is primarily used in gearing to:

A) Improve fatigue strength of the gear tooth in the root fillet;
B) Increase surface fatigue life to reduce pitting and increase durability.

Both of these effects are shown in Figure 6.



Tensile and shear stresses cause pits and fatigue cracks.

Fig. 6

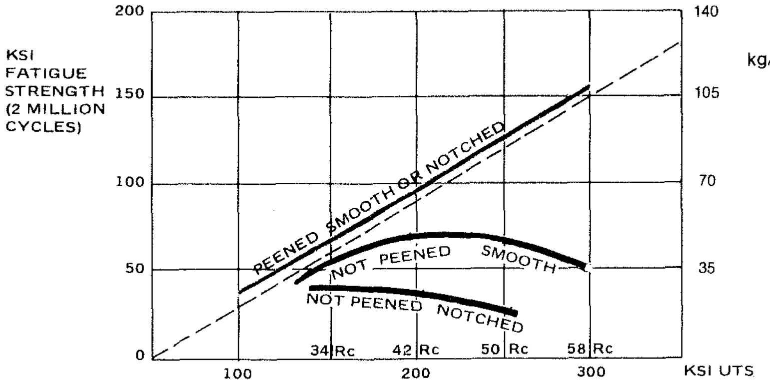
Side benefits from peening also include:

C) Aiding in the lubrication of the gear or gear system;
D) Elimination of continuous horizontal lines on the gear tooth flank produced by various gear machining methods that can be removed by peening in the "green" state. (Usually the surface finish produced by this technique will be an 83 RMS finish or higher, but this will vary with the initial gear hardness prior to the peening.)

IMPROVING FATIGUE STRENGTH OF GEAR TEETH

Since a gear tooth is essentially a cantilevered beam, it would be expected that failure due to a cyclical load would be expected in the root of the gear. Almen and Black (4) in their discussion of residual stresses in gear teeth, show that when fatigue fractures of the teeth occurred on failed automotive rear axle gears, the fracture always originated at the tension fillet. This fillet was on the same side of the gear tooth as the tooth loading.

Typically, gear designers will increase a gear's surface hardness to allow it to carry higher loads. However, hardening by heat treating requires gears to be remachined to compensate for dimensional changes during the carburizing, nitriding or other hardening processes. In addition, as tooth hardness increases above 43 Rc (approximately 200,000 psi), fatigue strength actually falls off. (See Fig. 7)(2).



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

Fig. 7

This most likely occurs due to increased notch sensitivity and brittleness. Whether a specimen that has not been peened is notched or smooth, noticeable decreases in fatigue strength can be noticed. As exhibited on the graph, a peened specimen will continue to have an increase in fatigue strength above 43 Rc.

Relating this to hardened gearing, by shot peening the root area of a gear after heat treating, both the benefits of improved wear characteristics due to increased hardness and increased fatigue strength due to the peening can be obtained. To develop the maximum compressive stress in the gear tooth due to the shot peening, the peening media should be as least as hard as the part being peened. Significant decreases in fatigue strength will be noted if the hardness of the peening media does not at least equal the hardness of the target material.

An important point to consider in gear design is the amount of residual tensile stress produced on the gear tooth profile and root due to grinding. Since the tensile stress from the bending load is usually greatest in the root fillet, the practice of grinding root fillets should be avoided, especially in highly stressed gears. However, these tensile stresses can be overcome by shot peening to introduce compressive stresses.

Seabrook and Dudley(5) in their conclusions indicate that shot peening is significantly beneficial in all cases except that of a nitrided steel surface which showed moderate results. Shot peening through hardened pinions can yield as much as 30 per cent improvement in fatigue limit.

Lloyd's Register of Shipping(6) allows an increase in tooth loading for both wear and strength up to 20 per cent for controlled shot peening. The term "controlled" is extremely important as Dudley and Seabrook (5) state that poor processing can yield a strength lower than a non-shot peened gear.

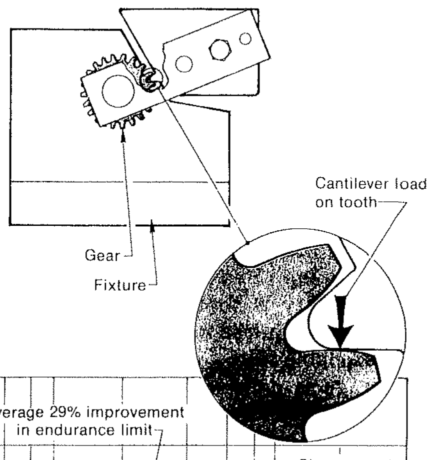
A typical test was run and the results are shown below. (See Fig. 8)(1).

Improving Endurance Limit with Shot-Peening

In a typical test of shot-peening, the endurance limit of a set of gears was improved by 29%. For the test, several gears were forged from the same bar of 4118 steel, carburized together to produce a 0.025 to 0.035-in. case, marquenched in 400°F oil for 10 min, air cooled, and tempered. Metallographic tests (after the fatigue tests) showed that the gears were as identical as commercially possible.

Half the gears were then shot-peened, the remainder left unpeened, and four of each type were run in a single-tooth bending fatigue test. The shot-peened gears proved to have an endurance limit much higher than that of unpeened gears. Average endurance limit was 3,025 lb for the peened gears and 2,350 lb for the unpeened gears, an improvement of 29%. Since all possible mechanical and metallurgical variables were held constant during the test, shot-peening was the only factor accounting for the increased endurance limit.

Test Set-Up



Test Results

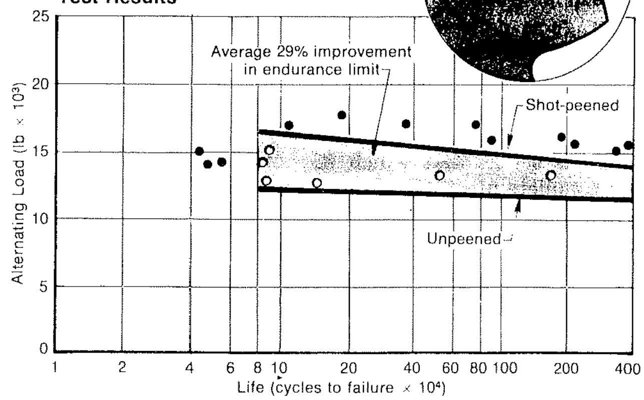
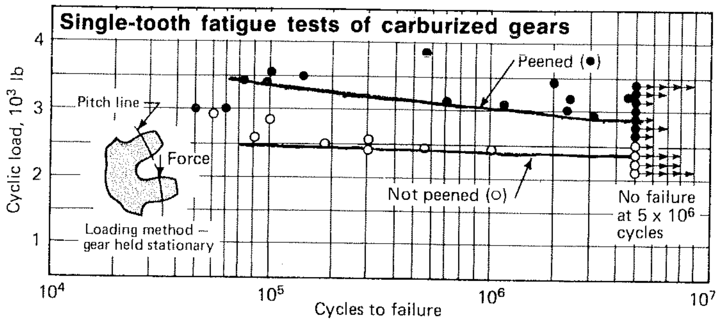


Fig. 8

Similar results are shown in Fig. 9 (3) for another example.



Carburized planet gears (4.8 DP with 1.4-in. faces), from the same 4118 stock, showed increased load capacity when shot peened.

Fig. 9

Figure 10 (3) shows the correlation of shot peening on some materials and treatments.

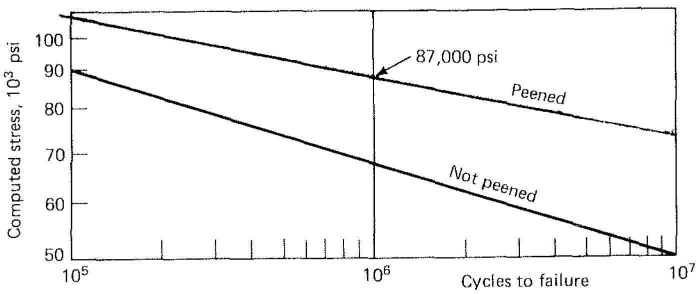
Material and treatment	**Fatigue limit, 10³ psi**	
	10% failure	**50% failure**
Carburized 9310	51	55
Carburized and shot peened 9310	58	60
Induction hardened 4340	38	44
Induction hardened and shot peened 4340	42	45
Induction hardened 4140	36	—
Induction hardened and shot peened 4140	40	—
Through-hardened 4340 at R_c35	30	—
Through-hardened and shot peened 4340 at R_c35	36	—
Through-hardened modified 4340 at R_c42	41	—

Fig. 10

Most noticeable increases in peened versus non-peened gears are shown for the through-hardened gearing; however, Seabrook and Dudley (5) showed a 33 per cent increase on induction hardened 4140 material.

Induction hardening and carburizing processes do produce some residual compressive stresses, however, not of the magnitude exhibited by shot peening.

In situations where a gear system may not have had gearing peened, significant uprating of the system can be accomplished if other components of the system are able to handle the increased loading. See Fig. 11 (3).



Shot peening can stretch fatigue lives of carburized gears or allow designers to use more compact transmissions for large loads.

Fig. 11

According to one study (3), using shot peening in a gear system and changing from a 300 BHN steel to a fully hardened steel of about 57 Rc with shot peening can halve a gear box's length, width, and height. Normally, peening of the total gear tooth is done. However, unless the application requires extremely smooth operation, peening of the root of the gear only is not recommended as increased costs would be produced by additional masking of the flanks. Peening does increase the roughness of the surface of a tooth, but it becomes less noticeable as the hardness of the gear increases.

Proper shot size selection is important to assure proper coverage. The shot size normally selected has a diameter no greater than half the radius of the fillet. (Other variables regarding shot hardness and size may enter into the specification of shot peening parameters.)

GEAR DURABILITY AND PITTING

Surface fatigue life can also be improved by shot peening. Pitting is caused in gear teeth by shear stresses below and parallel to the tooth surface. Since gears mesh with a rolling action along the pitch line, slip above and below the pitch line can be generated as high as 40 per cent. As a result of this slip, tiny cracks can develop under the surface at a depth of above .006 in. below the surface. These cracks propagate outward and toward the gear tooth surface until a thin wedge of metal breaks away, leaving the pit. Since cracks will not propagate into a layer of compressive stress, by peening to a depth of .007 to .008 inch, pitting can be prevented. Tests by NASA in studies by Townsend and Zaretsky (7) show an increase in surface pitting fatigue life of 1.6 times that of non-shot peened gears. Residual stress measurements and analysis indicated that the longer fatigue life is a result of the higher compressive stress produced by shot peening.

SHOT PEENING AND GEAR LUBRICATION

Since shot peening produces small indentations on the surface of a gear tooth, these now become tiny pockets or reservoirs. These surface reservoirs aid in the retention of lubrication, reduce fretting and scoring, and reduce operating temperatures.

SHOT PEENING TO REMOVE CONTINUOUS MACHINING MARKS

A technique that can be used in gears failing along continuous lines occurring across the face of a gear tooth produced by machining is to peen the surface of the tooth in a "green" state, and then to follow with the heat-treating process. The peening will eliminate the continuous stress risers produced by the machining marks and transform them to a homogeneous dimpled surface. This has been proven and is demonstrated in a paper by Robert Buenneke (8).

Since the heat-treating process will remove the benefits of the compressive stresses but not affect the dimpled surface, it is necessary to repeen the gear after the hardening process. The secondary peening operation will reintroduce the compressive stresses, but at a higher magnitude (due to the relationship of the compressive stress being at 50-60 per cent of the ultimate tensile strength of the material).

ADDITIONAL CONSIDERATIONS FOR GEARING

Shot peening is normally the last machining operation performed on a gear. Lapping or honing can be done after peening to the peened surface, but material removal must be limited to no more than ten per cent of the depth of compression. Grinding of a peened surface is not allowed because the heat generated by the grinding may relieve the compressive stresses. Temperature control of the lapping or honing operation is critical.

If the roughness of the tooth flanks produced by the shot peening is objectionable, the flanks may be shaved (rather than masked before peening), but again, proper coolant temperature maintenance is important.

Shot peening will not significantly increase the hardness of carbon steel and as a result, will not affect the ultimate tensile strength of the material. If the material is a type that is readily work hardenable, then increases in hardness along with subsequent increases in ultimate tensile strength can be expected.

SHOT PEENING CONTROLS

As with any machining process, it is necessary to have control techniques that can assure proper performance of the peened part. There are no known production techniques of measuring compressive stresses; however, lab experiments using X-ray diffraction can substantiate the stress distribution curves showing the magnitude of compressive stress and depth of compression. There are three points of the shot-peening process that must be adhered to to assure proper part performance. These points are the ability to determine and maintain proper intensity; shot integrity; and, to properly judge coverage in the peened area.

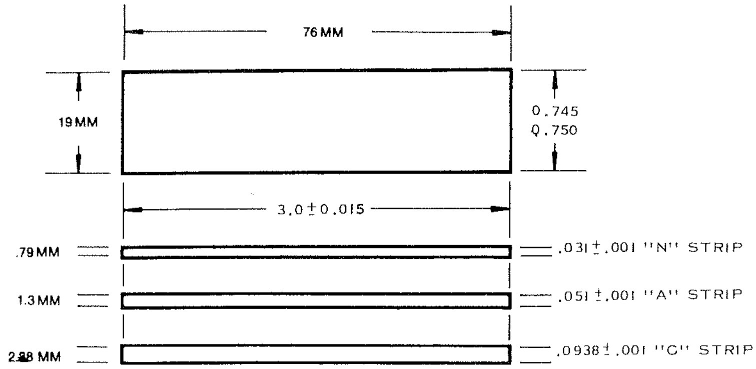
INTENSITY - This control point is gauged by strips known as Almen strips. There are three types which are used to determine the various ranges of intensities. These are the "N", "A" and "C" strips (See Fig 12).

These strips are a spring steel SAE 1070 material uniformly hardened and tempered to a 44-50Rc. These strips are used to calibrate the peening equipment. For each calibration test, several Almen strips of a single thickness (N, A or C) are clamped to a test fixture known as an Almen block and exposed to the shot stream for varying periods of time. When the strip is removed from the block, it will curve upward towards the side which has been peened (See Fig. 13).

The arc height is measured on each strip using an Almen gauge, as shown in Fig. 14. The longer the strip has been exposed to the shot stream, the greater the deflection of the strip. If an "A" strip is exposed to a shot stream to produce a deflection of .015", the intensity is a .015A intensity. The measured strips are then used to plot a saturation curve which plots the arc height versus the exposure time. For a particular machine set-up, the region being sought to develop an ideal exposure time for a specified intensity is the beginning of the saturation range. This saturation range is defined by military standards (9) as the area on the curve where there will be less than a 10 per cent increase in the arc height of the strip after doubling the exposure time (See Fig. 15).

Calibration fixtures for gearing may often be formed from the gear itself. As shown in Fig. 16, the block has been mounted in the plane to be peened on the gear. This gear will be used for calibration purposes only.

The saturation curve is an important part of the controls used because proper intensity is important in determining the success or failure of a part in fatigue. Too high of a shot mass or velocity may damage the gears, while too low an exposure time will produce residual compressive stresses that are too low (See Fig. 17).



TEST STRIP SPECIFICATIONS

Fig. 12

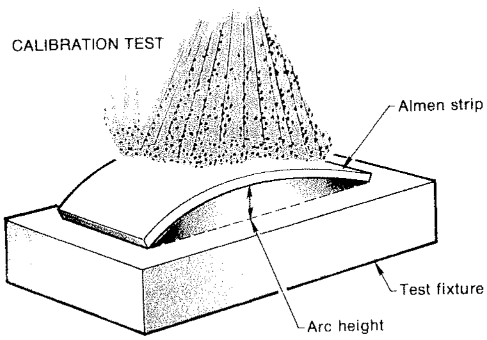
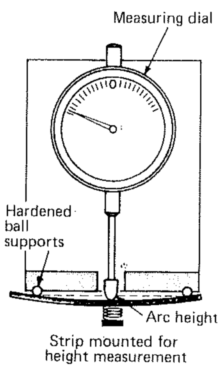


Fig. 13



Almen gauge

Fig. 14

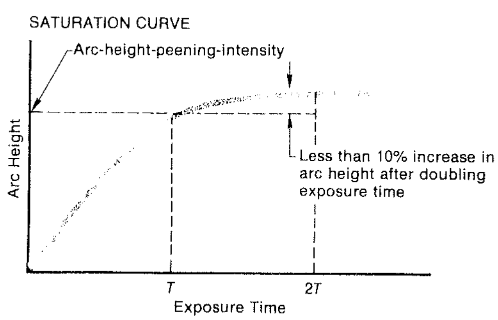
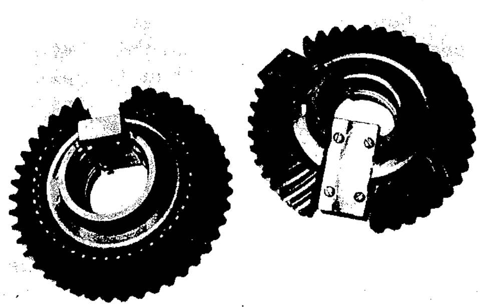
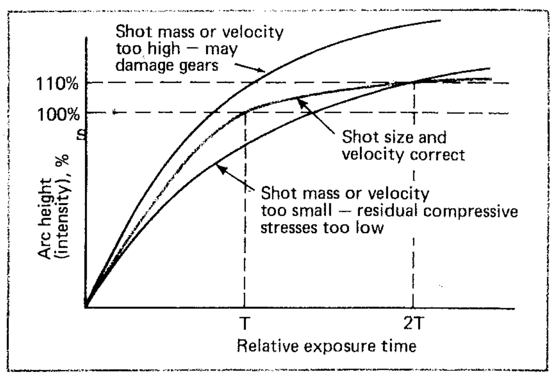


Fig. 15



Gear Calibration Fixture

Fig. 16

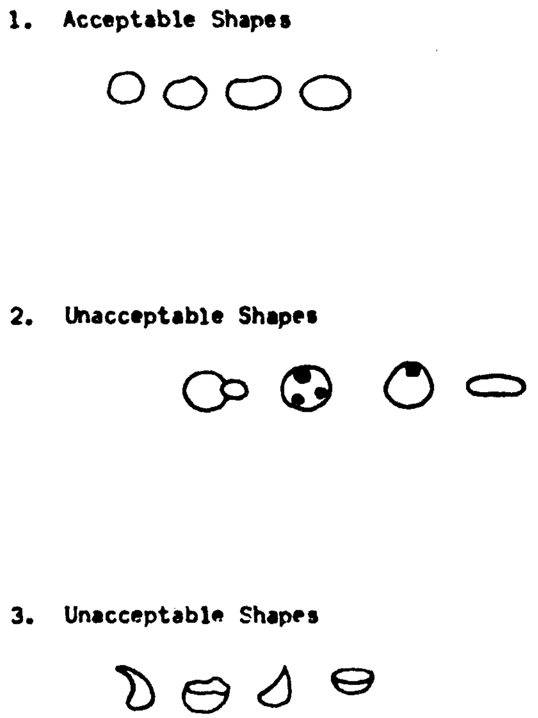


Improper saturation curves compared to correct curve

Fig. 17

MAINTENANCE OF SHOT INTEGRITY - The second control area is the maintenance of size and shape of the peening media. Media used in shot peening should be spherical and non-porous (See Fig. 18).

When metal strikes metal, something will break down. In a shot-peening operation, the shot will degenerate into unacceptable shapes and sizes. If these shapes are used in the peening operation, stress risers can be produced on the peened surface due to the sharp-edged configurations. In addition, shot mass is reduced with a proportionate decrease in intensity.



Acceptable and Unacceptable Peening Media Fig. 18

It is mandatory that shot be inspected during regular intervals to prevent shot deterioration to unacceptable shapes and sizes. Since shot is expensive, typically as it degenerates shot will be removed from the machine and classified. This is done in a machine known as a classifier, which has a series of screens located below a hopper which will sift the improper sizes from the good sizes. After the shot has been separated by size, it is metered into a spiral. Shot that is spherical will roll to the outer edge of the spiral as it moves down and will drop off into the next lower spiral. Shot that is of an improper shape cannot roll and will be confined to the first spiral. By the time the shot has traveled through the screens and the spiral, it will be sorted by size and shape.

COVERAGE - The third control area is coverage. A surface that is to be peened should have a complete dimpling of the surface, as shown in Fig. 19B. The surface should never look like Fig. 19A. In Fig. 19A there are many areas that have not been covered with indentations. As a result, these areas are surrounded by compressive stresses, yet they are areas of tensile stress.

If a root fillet on a gear had only partial coverage, the flat or undimpled areas would now carry higher tensile stresses and subsequent premature failure of the part is possible. On harder surfaces, this dimpling of the surface becomes more difficult to detect by the naked eye. Two acceptable techniques have been developed to determine proper coverage. These are·

A) Visual examination by the use of a 10X magnifying glass;
B) Examination by Dyescan using the Peenscan process.

Visual examination by a 10X glass is self-explanatory. The observer inspects the peened surface to check for full coverage.

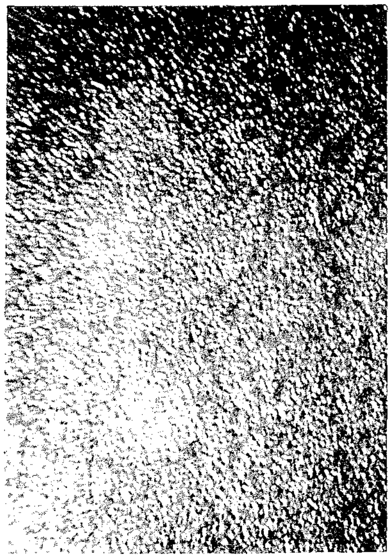
Inspection by the use of Dyescan is accomplished by coating a part in the area to be peened with the Dyescan liquid. Under normal lighting the surface will appear glossy, but under "black light" the Dyescan coated surface will "glow." After a machine has been calibrated for intensity and shot integrity, the Dyescan coated part is placed in the machine and peened. The Dyescan can only be removed by a direct impingement on the surface or by an impingement no more than 15 degrees of dead center.

After the surface of the part has been peened, the part is removed and inspected under "black light." The areas that have not been peened correctly will "glow," and indicate incomplete coverage (See Fig. 20).

Percentage of coverage can also be determined by observation at the surface. Coverage less than 100 per cent is unacceptable and increased peening time will be necessary (See Fig. 21).

Only the initial set-up piece and selected pieces during the part run are inspected by Peenscan.

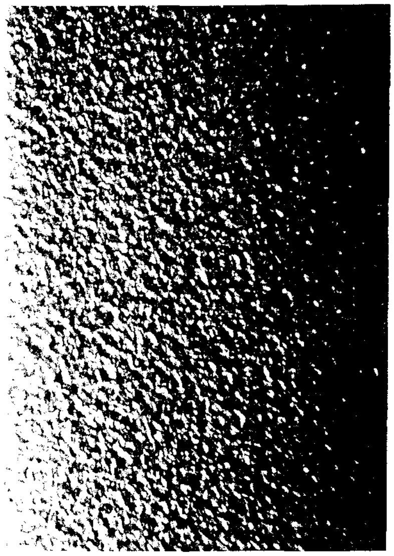
PARTIAL COVERAGE



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

A

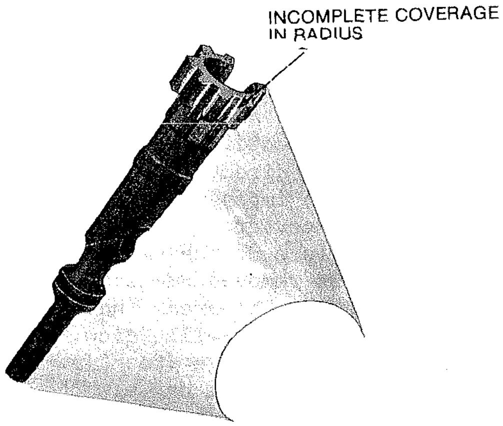
FULL COVERAGE



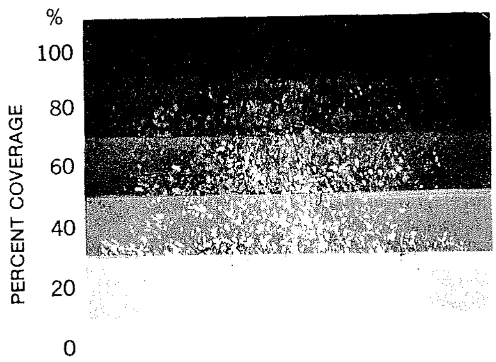
COMPLETE DIMPLING OF ORIGINAL SURFACE. ORIGINAL SURFACE COMPLETELY OBLITERATED BY OVERLAPPING DIMPLES.

B

Fig. 19



Detection of Improper Coverage
Fig. 20



Coverage determination of Almen strips.
Fig. 21

ADDITIONAL CONTROLS - The state-of-the-art in peening controls indicates a trend toward the use of microprocessors for data storage and display of part set-up. This, coupled with interlocks to the process machinery, sensors to monitor shot flow, turntable rotation and other key control areas are part of a new generation in peening controls. Violation of the monitoring points will signal a microprocessor, which will automatically shut down the process.

SUMMARY

In gearing, shot peening is effective in the following areas:

A) Increasing fatigue strength;
B) Increasing gear life by decreasing problems with reduced durability caused by pitting;
C) Aiding in lubrication of the gearing;
D) Eliminating stress risers along the tooth flanks caused by machining marks. By producing a homogenous dimpled surface and peening in the "green state " stress risers can be eliminated.

Shot peening is an effective tool in these areas if proper control techniques are used. These control techniques are:

A) The ability to correctly determine the peening intensity;
B) The ability to remove improperly sized and shaped media;
C) The ability to assure complete coverage of the area to be peened.

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