BOOSTING GEAR LIFE THROUGH SHOT-PEENING

Shot-peening is seldom specified in original gear designs. Yet it can improve the life and load-carrying capacity of gears by as much as 20%, often without adding appreciably to cost.

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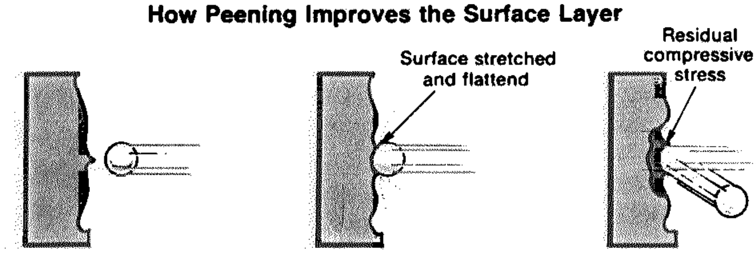
SHOT-PEENING creates a compressive layer of material on the surface of metal parts. In gears, this layer improves load-carrying capacity by increasing the bending fatigue strength of the teeth. It also reduces surface fatigue and pitting by impeding the spread of subsurface cracks.

The potential benefits of shot-peening vary for different types of gears. With some high-performance gears, for instance, shot-peening improves strength and life while adding only about 1% to the total manufacturing cost. The process can also reduce material costs by allowing the use of less-expensive, lower-strength materials.

On the other hand, shot-peening can add as much as 10% to the cost of mass-produced gears operating with moderate loads. Since these gears may not need the extra capacity produced by shot-peening, higher costs may not be justified. Also, peening increases the surface roughness of gear teeth, which may cause problems in applications requiring extremely smooth operation. This roughness can be avoided by masking the tooth flanks and peening only the root area or by shaving the flanks after peening. However, these processes further add to production costs.

So the benefits of shot-peening must be weighed against increased costs. All too often, such evaluations are performed only when a gear is tested and found wanting. More prudent practice is to consider shot-peening during the original design process.

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.

Why Peening Helps

Shot-peening is the bombardment of a metal surface by high-velocity particles. As each particle strikes the work piece, it deforms the surface plastically, stretches the surface radially, and induces tensile stress. When the particle bounces off, tensile stress is relieved, and because of the plastic deformation, an overall compressive stress is left in the surface. This residual stress offsets the detrimental effects of the applied tensile loads.

Newly manufactured, unpeened gears contain concentrations of residual tensile stress introduced during manufacturing. The highest concentration of stress is in the tooth fillets at the gear root. This area is also the most highly loaded when a gear is running and is subject to bending fatigue failure. If the combination of applied load and residual tensile stress is high enough, the gear fails prematurely.

Shot-peening removes the residual tensile stress and replaces it with a compressive stress. Because fatigue failure never starts in an area under

Short Course in Shot Peening

Correct shot-peening is not an easy task. The basic parameters of the process—stress, depth of penetration, and shot coverage—depend on a number of variables including shot size and hardness, exposure time, shot velocity, and angle of shot impingement. In addition, the relative motion between shot stream and part must be synchronized closely to provide uniform and reproducible coverage.

The process is simplified by a system of standardization based on the Almen strip. This strip is a piece of standard spring steel (SAE 1070) peened on one side only. When exposed to the shot stream, the Almen strip bows convex to the stream. The amount of bow is measured as the arc height and serves as a gage to calibrate the peening equipment.

The standards provide for three thicknesses of test strips—designated *A*, *N*, and *C*—to provide three different sensitivities to the peening process. When the strips are shot-peened, they bow by varying amounts, depending on their thickness. Thus, three different intensity ranges can be calibrated.

In the initial set-up, an Almen *A* strip is shot peened and the arc height is measured. If arc height is between 0.004 and 0.020 in., the *A* strip is used for calibration. If the arc height is less than 0.004 in., the *N* strip is used; it provides readings three times higher than those of the *A* strip. If arc height is greater than 0.020 in., the *C* strip is used; it provides readings 0.3 times those of the *A* strip.

To calibrate the peening equipment, a series of Almen strips are peened. All variables except exposure time are held constant, so a time-to-arc-height curve can be plotted. At a particular time, a saturation point is reached where the arc height barely increases with longer exposure times. If the arc height increases less than 10% with a doubling of exposure time, a point called the arc-height peening intensity (or saturation) is reached, and the calibration curve is complete. The curve now serves as a guide for specifying and reproducing the correct amount of peening for production parts.

If the arc-height peening intensity cannot be produced in a reasonable amount of time, either shot velocity is too low or shot size is too small. Coversely, if this point is overshot, shot velocity is too high and parts may be damaged.

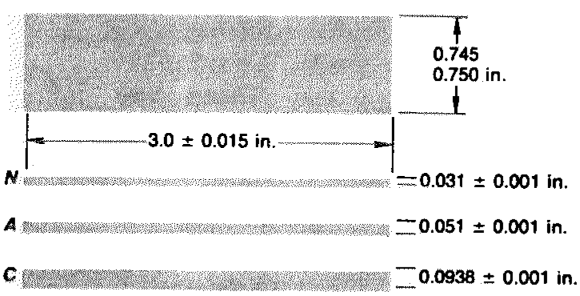
A typical peening specification designates an arc height range such as 0.010 to 0.014-*A*, which means an arc height between 0.010 to 0.014 in. as measured on an Almen *A* strip. Production parts are then peened for a time equivalent to that required to create a 0.010 to 0.014-in. arc height—as determined on the calibration curve.

Gears require maximum depth of compressive stress, so they must be covered uniformly and completely. Thus, full coverage is specified; that is, the gear must be exposed to the shot stream long enough to exhibit complete plastic flow.

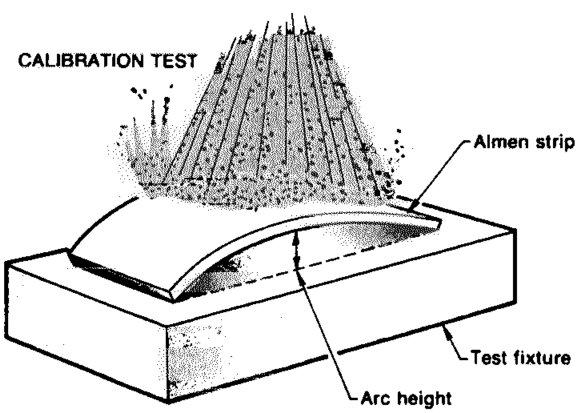
The time required to saturate the Almen strip is not necessarily the same as the time required to saturate a part. If part hardness is appreciably different from the 44 to 50 Rockwell C hardness of the strips, the time required to saturate the part also varies. For instance, a carbuized part requires more time to reach 100% coverage, while a softer part needs less time.

Calibrating the Peening Equipment

STANDARD ALMEN STRIPS

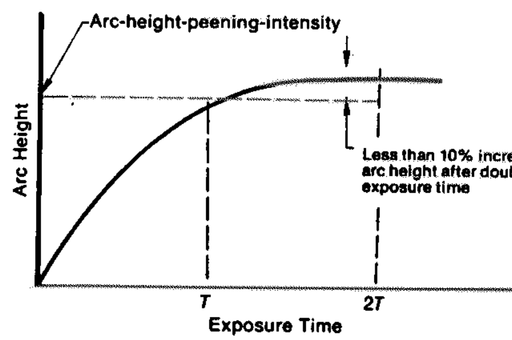


Almen strips come in three thicknesses to provide three different sensitivities to shot-peening. When exposed to the shot stream, the strips bow by different amounts, depending on the thickness.

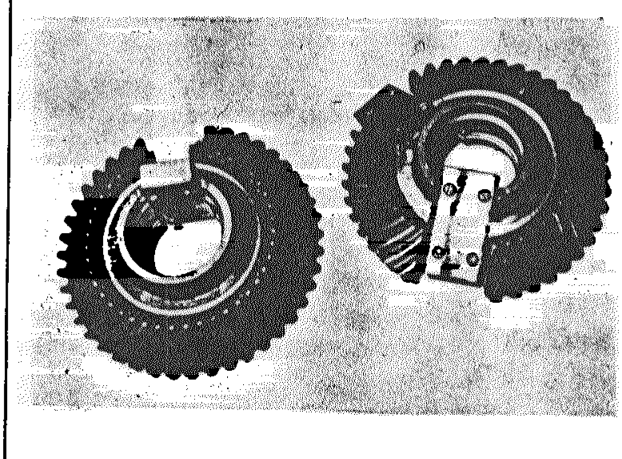


For each calibration test, several Almen strips are clamped to the test fixture and exposed to the shot stream for varying periods. The strips curve convex to the shot stream, and the arc heights are plotted vs exposure time.

SATURATION CURVE



The saturation curve indicates the intensity and time of exposure needed to produce uniform depth.



Calibration fixtures for gears are often formed from the gear itself. More than one Almen-strip mounting surface usually is required to determine the optimum angle of impingement.

compression, the applied tensile load must first overcome the residual compressive stress before fatigue is initiated. Thus, the objective of the shot-peening process is to produce a residual compressive stress high enough to counteract the effects of the applied load.

Gear teeth also are subjected to high shear stresses on the tooth surface to a depth of about 0.006 in. Typically, small cracks develop beneath the surface at this depth and propagate outward in a V-shape. When the crack reaches the surface, a piece of metal chips out, forming a tiny pit.

Pitting can be prevented by shot-peening the gear teeth to produce a compressive skin deeper than this critical level of 0.006 in. (usually to about 0.008 in.). The subsurface high-shear area is then encased in an area of compression that retards crack propagation.

How Much More Load?

Shot-peening improves gear performance in two ways. Strength improves because peening increases the bending strength of the tooth fillet area; wear resistance improves because the compressive skin resists pitting. The quoted figure of 20% improvement in both strength and wear is supported by field and laboratory tests.

However, the results of these tests are often confused especially if the gears are highly loaded or run for extended periods. These gears can fail by means other than bending fatigue in the tooth fillet. So a quantitative evaluation of shot-peening is difficult unless failures from bending fatigue are isolated.

As a result of this problem, the single-tooth bending fatigue test has been developed to evaluate the worth of shot-peening. This test isolates bending fatigue at the fillet root from other types of failure.

The test principle is simple: Each gear tooth is treated as a cantilever beam, and a load is applied to the outer portion of the tooth until it fails. During the test, one tooth is loaded with an alternating load to failure or to a minimum of 5 to 10 million cycles. The gear is then rotated two or more teeth and retested.

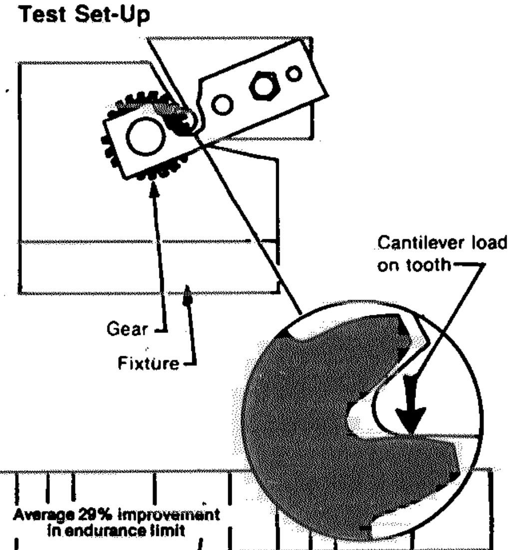
If the previous tooth failed, this tooth is cycled at a lower load; if the previous tooth did not fail, this tooth is cycled at a higher load. In this way, several teeth on one gear can be tested, and the effects of variables such as metallurgy and heat treatment can be minimized.

Improving Endurance Limit with Shot-Peening

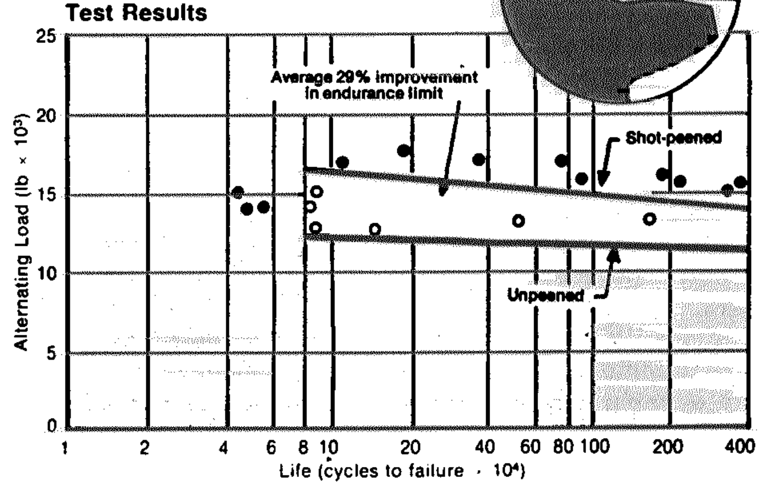
In a typical test of shot-peening, the endurance limit of a set of gears was improved by 29%. For the test, several gears were forged from the same bar of 4118 steel, carburized together to produce a 0.025 to 0.035-in. case, marquenched in 400°F oil for 10 min, air cooled, and tempered. Metallographic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

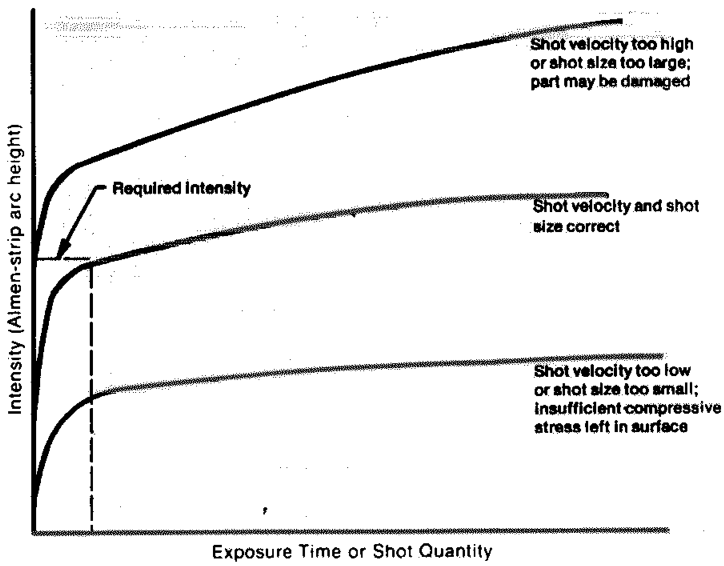
Test Set-Up



Test Results



Peening Intensity Varies with Exposure Time



To ensure that the mechanical properties of a gear are improved reliably, the intensity of the shot stream must be controlled carefully. Intensity (measured as the arc height on an Almen strip) depends on exposure time, shot velocity, coverage, and the type of shot. The optimum balance among these variables produces uniform coverage in a reasonable amount of time.

How Much Peening?

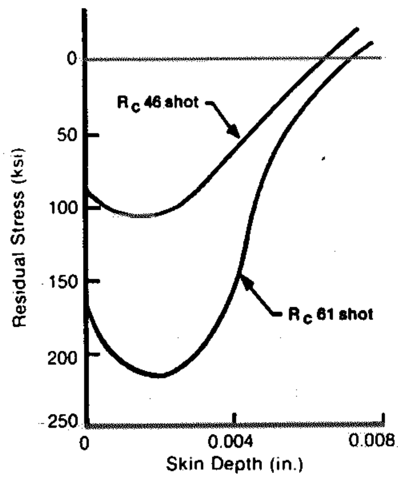
To ensure that shot-peening improves the mechanical properties of gears, the peening intensity must be controlled accurately. Generally, the factors controlled are shot velocity, exposure time, uniformity of coverage, and shot composition and size.

Shot velocity and exposure time are determined during calibration of the peening equipment. (See *Short Course in Shot-Peening*.) Basically, the proper velocity is that which produces the required intensity in a reasonable time.

Coverage is defined as the percentage of the surface area struck by peening particles at a given time or during one operating cycle. A value of 100% coverage is set as that which causes complete plastic flow in the entire surface of the peened object.

Generally, gears require 100% minimum coverage to ensure a uniform depth of compressive stress. However, gear shape and the direction of the shot stream sometimes make it impossible to cover a part completely in one pass. Therefore, higher coverage (up to 200%) is often specified to ensure uniform coverage.

Hard Shot Leaves a Deeper Skin



Generally, harder shot produces deeper compressive skins and higher residual stresses on case-hardened, carburized gears. Shot hardness must be at least as hard as the part so the maximum stress is produced. Normally, shot hardness is specified to produce a peened depth of about 0.008 in. Graph represents 1045 steel gears.

Steel shot with a hardness of 45 to 55 Rc is commonly used for gears. However, with the increasing use of high hardness steels (50 Rc and above) in gears, special hard steel shot often is required. For example, case-hardened, carburized gears must be peened with 55 to 65 Rc shot to produce the required compressive stress and depth of skin. Generally, the harder the shot, the deeper the skin and the higher the stress.

Shot diameter should be no larger than one-half the smallest fillet radius on the surface to be peened. Larger shot may not penetrate the fillet area.

Another important consideration is the quality of the shot. Whatever the material the particles must be well-conditioned, spherically shaped, and uniformly sized. Broken or deformed particles must be eliminated because their sharp corners can damage the surface and cause stress risers.

The angle of impact between shot stream and peened surface has a considerable effect on intensity level. Generally, maximum intensity is produced by a stream directed slightly more or less than perpendicular to the part. With most gears, a single shot stream may not provide equal intensity on all parts of the surface. Therefore, the blast stream should be directed from two or more positions.

Normally, gears are rotated within the shot stream to provide uniform coverage. Speed of rotation is not critical as long as all teeth are covered equally. Moderately sized spur and helical gears are usually exposed to the shot stream in the indexed position. This set-up allows the gears to be stacked for high-volume peening. The main blast stream is horizontal to the gear stack.

With bevel gears, the shot stream should be horizontal to the root cone. Large gears with wide faces are rotated about their own axis. The center of the shot stream is aimed at the root fillet and flank. MD