Shot peen gears for longer life

Since compressive stress slows fatigue cracking, designers are turning to shot peening to increase the operating lives of gears

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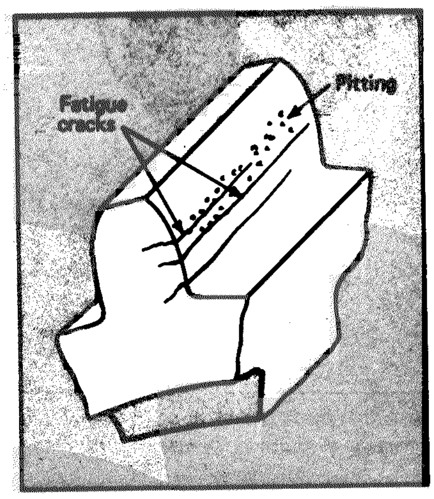
The trend towards smaller, stronger, higher-capacity gear transmissions has inevitably increased interest in all forms of metal hardening and fatigue-life extension. Designers of high-power marine and turbine propulsion systems are not alone in demanding compact gears that resist fatigue and corrosion better than their predecessors. New designs for speed reducers, gear motors, agricultural machinery and aircraft accessories all call for lighter gears that can operate under load day in and day out without failure.

Manufacturers have long looked to heat treatment when they want higher performance from smaller gears. Unfortunately, higher performance doesn't always mean longer performance. Some decline in fatigue life often follows heat hardening. So gear users have been looking to shot peening to counter the drawbacks of heat treatment and boost gear life.

Auto makers have become accustomed to using this cold-working process to increase fatigue lives of springs and torsion bars as well as gears. And one firm that specializes in shot peening—Metal Improvement Co. (Paramus, NJ), a subsidiary of Curtiss-Wright Corp.—reports that the use of shot-peened gears is on the rise in other sectors as well, though many designers are not making full use of the process' advantages. (Some leading gear manufacturers do their own shot peening, but because the process demands special equipment and tight quality control, most peening is concentrated in independent specialized shops).

While most design courses cover the heat treatment of metals, few have much to say about mechanical cold working processes. As a result, say officials of Metal Improvement, few designers seem to know what benefits to expect from shot peening, and even fewer may be able to specify such things as the intensity of peening or compressive skin thickness that may be demanded by a given application.



1. Tensile and shear stresses cause pits and fatigue cracks

Making up for lost stresses

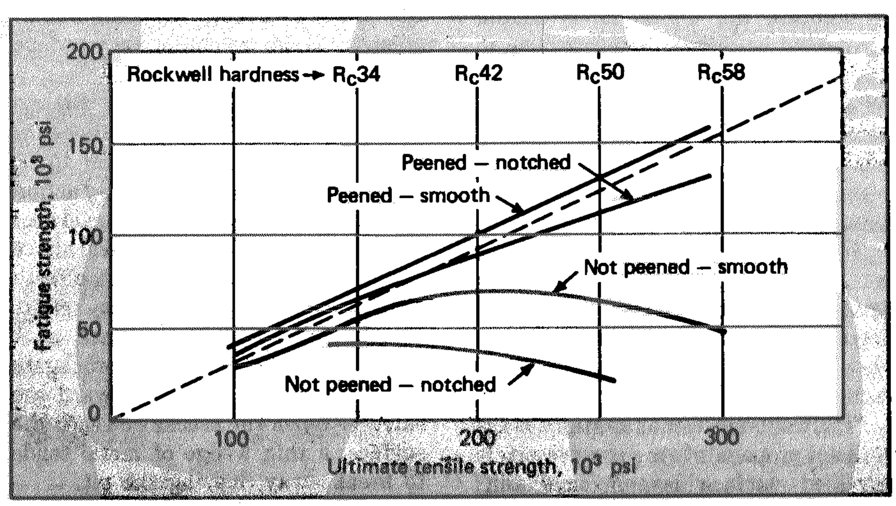
Tests by gear makers like General Electric (Lynn, MA) and Philadelphia Gear (King of Prussia, PA) have shown that increasing a gear's surface hardness lets it carry higher loads—which means that smaller gears can replace larger ones, saving weight and space in the housing as well as in the gears. According to one study, a shift from medium-hard 300 BHN steel (about R_c 32) to a fully hardened steel (about R_c57) can halve a gear box's length, width, and height.

Heat hardening takes its toll, though. To stay within quality tolerances, fully hardened gears must often be remachined after heat treatment to compensate for dimensional changes during the carburizing, nitriding, or other hardening processes.

Heat treatment itself may induce some undesirable residual stresses in addition to the beneficial stresses and the hardened case. Corrective post-treatment machining can remove some of the case and disrupt the beneficial stresses.

Moreover, fatigue strength can actually fall off a bit as heat treatment pushes the surface's ultimate tensile strength (and hardness) above 200,000 psi (R_c43), according to test results reported by the Air Force's Wright Air Development Center (Fig 2).

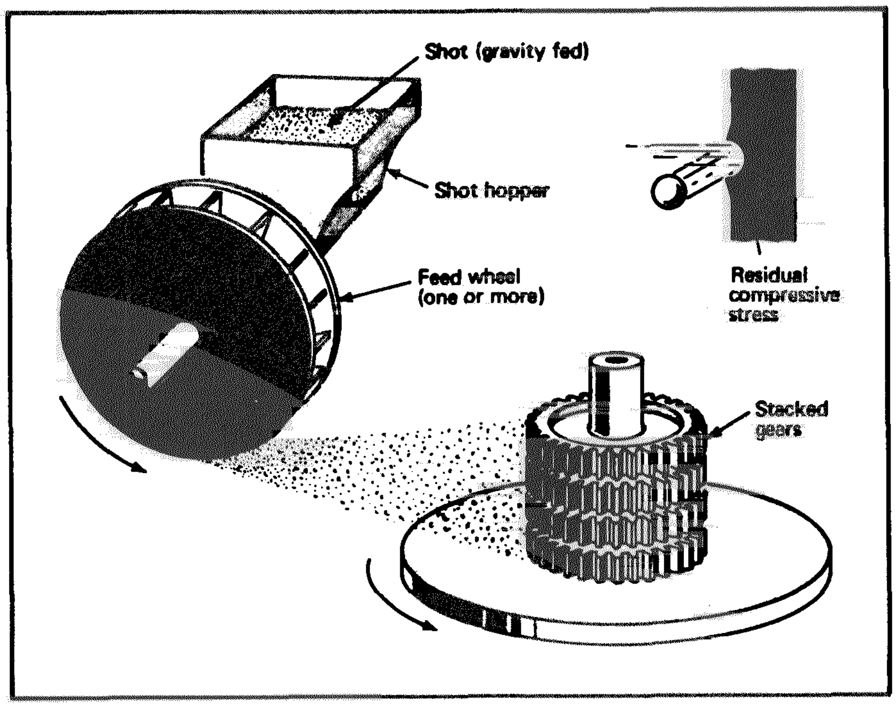
There is a solution. General Electric's test results indicate that shot peening can be an extremely useful



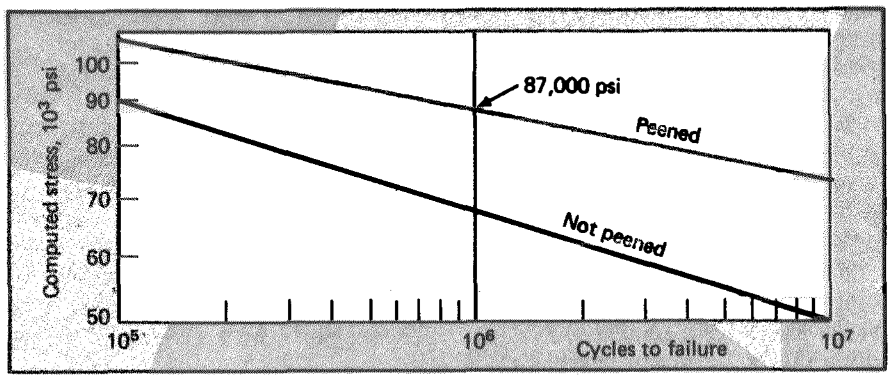
2. Shot peening keeps fatigue strength from falling as carburization boosts ultimate tensile strength, increasing capacity and life supplement to heat treatment—improving fatigue strength by nearly a third in some cases. In fact, GE researchers concluded, "Shot peening has been shown to be significantly beneficial in all cases [that is, supplementing carburizing, induction hardening, and through-hardening] except that of shot peening a nitrided nitriding-steel surface. Shot peening nitrided, low-alloy steels shows only a moderate improvement."

Other researchers have found that shot peening produces shallow indentations that may act as small oil reservoirs, supporting deeper, more stable lubricant films than smooth metal surfaces can possibly do. This may explain why some users of shot-peened gearing say their cold-worked transmissions run more quietly and suffer less surface scoring than unpeened gears.

Still other tests have shown that peening, when properly done, can increase the corrosion resistance of some gears and other components, notably those made of type 416 stainless steel (R_c36 to R_c42).



3. Shot flung from a centrifugal wheel rebounds from the metal surface, leaving a shallow "crater" and wear-resisting stresses



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

How it works

"Shot peening" is about as descriptive a name as one is likely to find. Hundreds of bird-shot-size pellets (usually of cast steel but sometimes of glass) hammer away at the metal surface of the workpiece. When the shot strikes, it deforms the top layer of metal, stretching it radially under tension to make a small, crater-like depression. When the shot rebounds, relieving the tension, the crater remains, along with some residual surface compressive stresses resulting from the metal's plastic deformation. (See Fig 3.)

The bombardment is angled to strike as perpendicularly as possible at the gear root fillet, where the greatest beam bending stresses concentrate under load. The shot shower may be aimed at the tooth faces as well.

"It's well known that a fatigue crack will not propagate into a compressively stressed surface layer," says Cliff Mehelich of Metal Improvement. "Because nearly all fatigue and stress-corrosion failures originate at the surface of the gear tooth, inducing a compressive layer produces tremendous increases in operating life."

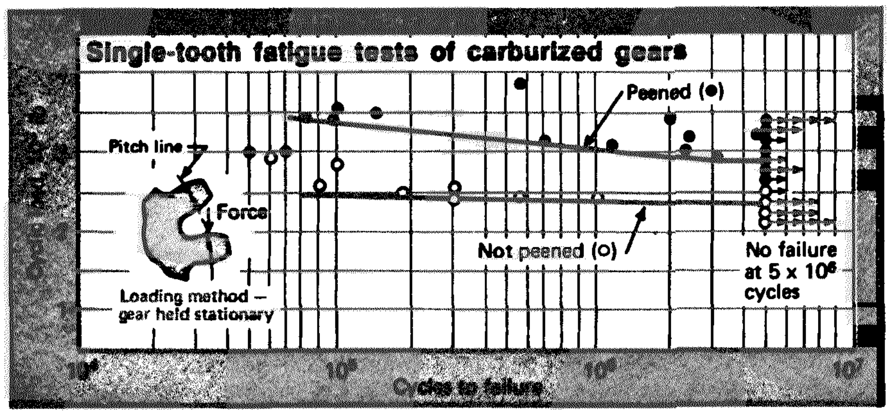
Gear teeth are also prey to pitting, which is caused by shear stresses below the tooth surface and parallel to it. Though gears mesh with rolling action along the pitch line, there is a good deal of slip (up to 40% in some cases) above and below the pitch line, as the teeth slide into and out of mesh. Tiny cracks can develop under the surface, at a depth of about 0.006 in. They propagate outward, angling slightly toward the surface. When the cracks do reach the surface, a thin wedge of metal tends to break away, leaving the pit.

Some automotive engineers are convinced that pitting might be prevented entirely by shot peening gear teeth to leave a compressively stressed "skin" 0.007 in. to 0.008 in. deep. Metal Improvement generally recommends shot peening to a depth of 0.008 in. for maximum load-carrying capacity. But shot-peening shops can produce compressive skins to a narrow range of specifications by varying the peening intensity—that is, by varying the velocity, the size of the shot, and the duration of the treatment.

30% improvement

Simple plots of working stresses vs cycles-to-failure (*SN* curves) show the effects of shot peening in the most straightforward and dramatic way.

One series of tests compared the performances of two sets of carburized



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

automotive gears. One set was shot peened, while the other was not (Fig 4). The *SN* curve for these tests shows that, for a standard service life of 1-million cycles, the peened gears could carry 30% more load than could the unpeened gears—87,000 psi for the cold-worked components against 67,000 psi for the unpeened gears. Obviously, a designer could count on transmitting a given power load for a given time through a smaller gearset by switching from case-hardened gears to gears that were both case hardened and shot peened. More dramatically, if the gear's size is unchanged, a designer can boost predicted operating life of gears running at 80,000 psi from 250,000 cycles to 3-million cycles, just by having the gear shot peened.

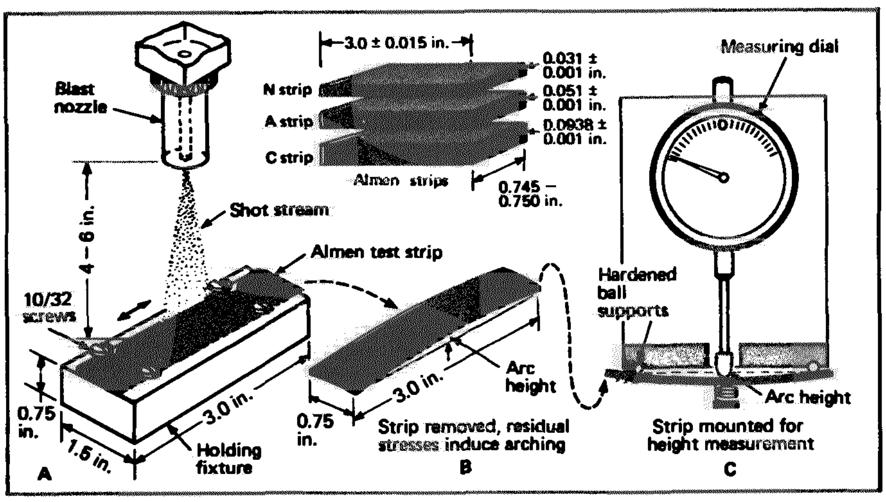
In another series of fatigue-life tests, individual gear teeth were loaded as cantilever beams (Fig 5). All the gears were forged from the same bar of 4118 steel; then they were carburized, quenched, and tempered to leave a 0.025-in. to 0.035-in. case. The test gears were then divided into two sets, and one set was shot peened while the other was not.

The gears were held stationary while a cyclic load was applied to the tooth at the pitch line to simulate the loading pattern of a running gear. The load was applied and released 5-million times or until the tooth failed. Then the gear was advanced two teeth (to avoid the aftereffects of the first test) and a second tooth was tested. If the first tooth survived the full 5-million cycles, the second tooth was tested under a higher load. If the first tooth failed, the second tooth was tested under a lower load.

As in the previous test, the shot-peened gears proved about 30% tougher than the unpeened gears. The average 5-million-cycle endurance limits were 3025 lb for shot-peened gears and 2350 lb for unpeened gears.

I. Materials, treatments, and fatigue limits

Material and treatment	Fatigue limit, 10^3 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	—

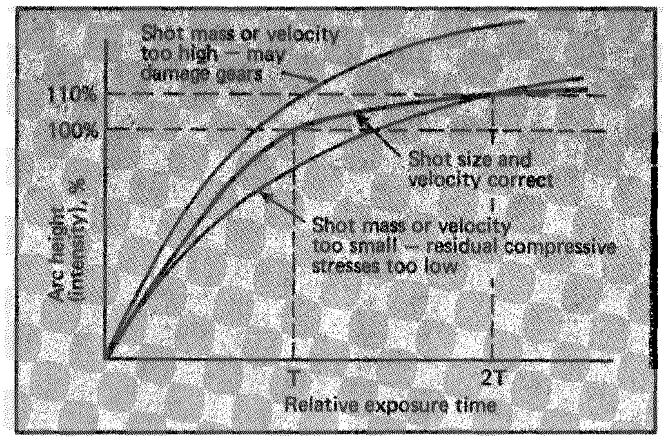


6. The shot blast leaves residual stresses that make the Almen test strip arch upwards. The arc height shows peening intensity

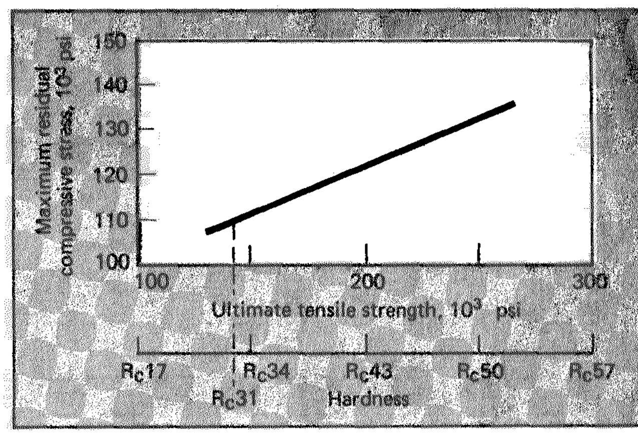
Planning the peening

The effectiveness of shot peening depends on a number of factors: the type, hardness, uniformity, diameter and mass of the shot; the velocity of the shot stream; the duration of the treatment; the distance from nozzle to workpiece; and the angle of impact. Fifty years ago, J. O. Almen of General Motors Corp. developed a method for quantifying all of these factors as the "intensity" of the shot treatment.

Almen's approach is simple. If a flat metal strip is clamped to a test block and blasted with shot, the residual surface compressive stresses will make the strip bow upward in the middle when released (Fig 6). The height of



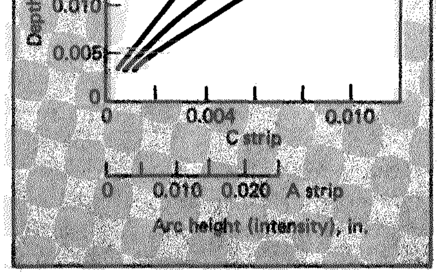
7. Saturation is reached when doubling exposure increases Almen strip height less than 10%



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

this bowed arc is an index of the induced stresses and the thickness of the compressed skin—namely, the intensity of the peening.

The Almen strip test, as it is called, uses three standard size strips to measure ranges of peening intensity as accurately as possible. All strips are 3.0 in. long and 0.75 in. wide. The most commonly used is the *A* strip, which is 0.051 in. thick. Lower shot-stream intensities are measured by the *N* strip,



8. Strip arc height corresponds to the stress skin thickness

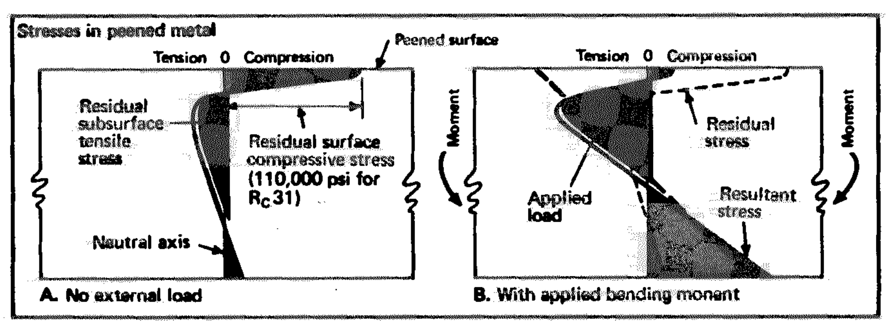
0.031 in. thick, and higher intensities are measured by the *C* strip, 0.0938 in. thick.

Whichever strip is used, the height of the final arc varies with the exposure time and the shot's size and speed. At some point, the strip is said to be "saturated": doubling the exposure time will increase the arc height—and the residual stresses—by no more than 10% (Fig 7).

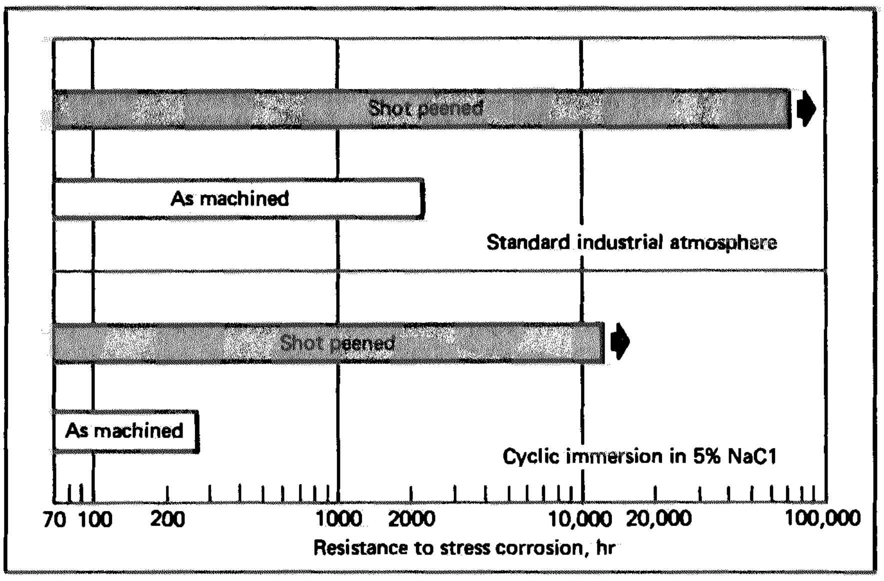
If the strip becomes saturated before the desired intensity or arc height can be reached, the shot is too small or its speed is too low. Conversely, if the intensity is too great, the shot is too big or its speed is too high. To attain the stress-skin depth specified by a designer, the shot-peening shop must run a thorough series of Almen tests on the proper material to establish the most effective shot size and speed.

For example, to achieve a compressed skin 0.010 in. deep in an R_c 31 alloy, the shot stream should be "tuned" to produce an Almen *A* strip arc height of 0.0085 in. (Fig 8). From this information, one can find the residual compressive stresses remaining after the metal has been peened (Fig 9). For an R_c 31 metal, the induced stresses will run about 110,000 psi.

The relationship between this induced compression and the tension produced by the load is crucial. In an unloaded, shot-peened beam or gear tooth in equilibrium (Fig 10a), the sum of the surface compressive moments and the subsurface tension must be zero. When an external bending moment is applied (Fig 10b), as when the gear is run under load, the resultant



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



11. By masking tensile stress, shot peening helps control stress corrosion in industrial and saline environments

stress (the solid curve) is the sum of the applied load (straight dotted line) and the residual stresses (dotted curve). As long as the peened surface remains compressed, it is protected against fatigue cracking.

Slowing stress corrosion

Aircraft manufacturers have begun using shot peening to control stress corrosion, a progressive decay accelerated by the combination of tensile stress and corrosive agents. The tensile stresses may stem from applied loads or residual stresses. The higher strength aluminum alloys are reportedly quite susceptible to such failures, though most other metals—stainless steel, titanium, and copper among them—are also prone to stress corrosion.

Since tensile stress promotes stress corrosion, it is not surprising that overriding compressive stresses should inhibit the process. Thus, shot peening has shown itself to slow such corrosive action. In one test, components were cyclically immersed in salt solutions (Fig 11). The lives of shot-peened aluminum parts were typically about 50 times longer than the lives of untreated parts.

A note about shot

The cast steel shot usually used for peening gears is made to several specifications. The harder the shot, the deeper the skin and the higher the residual compression. In general, shot with a hardness ranging from R_c 55 to R_c65 should be used for shot peening those gears that have already been carburized.

The quality of the shot can influence the saturation time. Most commercially available shot meets MIL S-851 or AMS 2430 specifications. Tests by Metal Improvement Co. show that such grades are sometimes too soft for treating high-strength parts such as gears. For these applications, the company recommends shot meeting MIL S-13165B specs, which prescribe close screening for uniform size, and limit the number and configuration of deformed shot.

The shot-peened layer should cover the gear surface uniformly. Simple visual inspection is not sensitive enough to show whatever "holes" may remain. To test, coat the part with a fluorescent tracer before peening. The MIL S-13165B specification (as amended in June 1979) recommends using a "Peenscan" process employing Dyescan liquid dyes, which may be painted, sprayed, or dipped onto the workpiece. The liquid dries to an elastic film that is visible under ultraviolet light. The film is checked before the part is shot peened, to make sure that the whole surface is covered; and it is checked again after peening, to ascertain that all of the coating has been hammered away. A shot shower that is too soft will not remove all of the film, and any islands of remaining dye indicate areas where the gear surface has not been completely covered.

International shot peening symposium

One indication of shot peening's growing importance is the forthcoming First International Conference on Shot Peening, slated to convene in Paris next fall. The four-day symposium is sponsored by two agencies of the French government: the Centre Technique des Industries Mecaniques (CETIM)—the technological center of the French metalworking industry—and the French Ministry of Industry.

Experts from 16 nations are scheduled to present papers. Dr. Henry Fuchs, a pioneer of shot peening and now professor emeritus at Stanford University, will give the keynote address.

The symposium will meet September 14 through 17 at the Tour Olivier des Serres, 78 rue Olivier des Serres in Paris. For more information, contact G.P. Balcar, vice president of Potters Industries Inc., 377 Route 17, Hasbrouck Heights, NJ 07604.