Improved Gear Life Through Controlled Shot Peening

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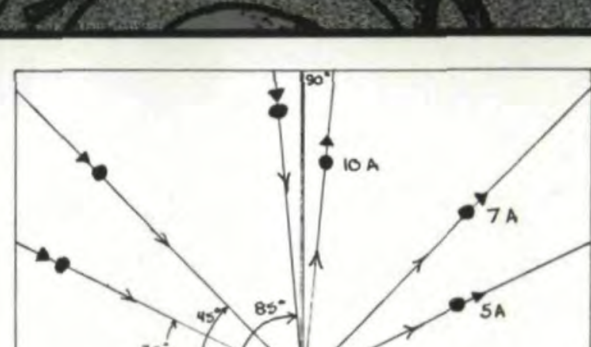

Fig. 2 – Almen intensities measured in Almen units – intensity being a function of size, mass, hardness and velocity. Note the intensity varies as the size of the angle of impingement varies.

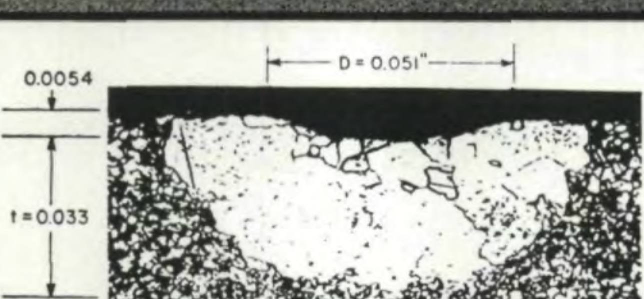

Fig. 1 – Effect of shot impacting a part at 90° impingement angle.(1)

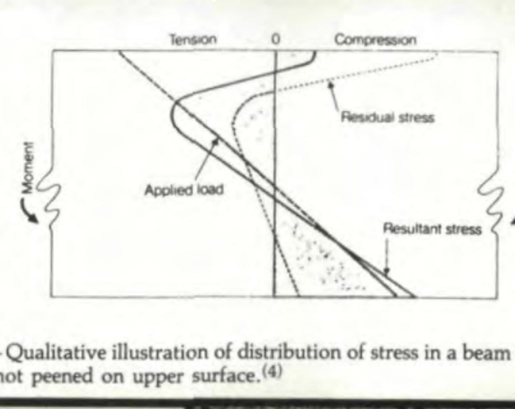

Fig. 3 – Qualitative illustration of distribution of stress in a beam which has been shot peened on upper surface.(4)

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 and pitting failure at the pitch line, as well as providing other benefits for gear designers and users.

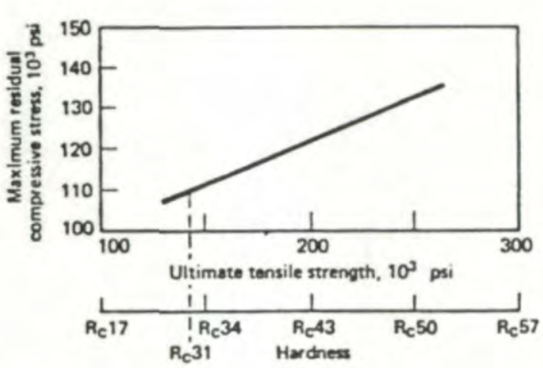

Fig. 4 – Ultimate tensile strength and surface hardness determine the residual stresses after peening.

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The search for greater gear life 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 and 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 phase 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 when 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, they induce a compressive layer in the material. The depth of the area affected is about equal to the diameter of the dimple, and the total affected surface area is about twice the size of the dimple.

In Fig. 1 we see the effect of shot which impacts the part at an impingement angle of 90°. As angles of impingement vary from 90° to 45° 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 deserve the closest possible control and is covered in more detail later in this article.

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 formed.

Fig. 3 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, 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 in 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% of the ultimate tensile strength of the base material. (See Fig. 4).

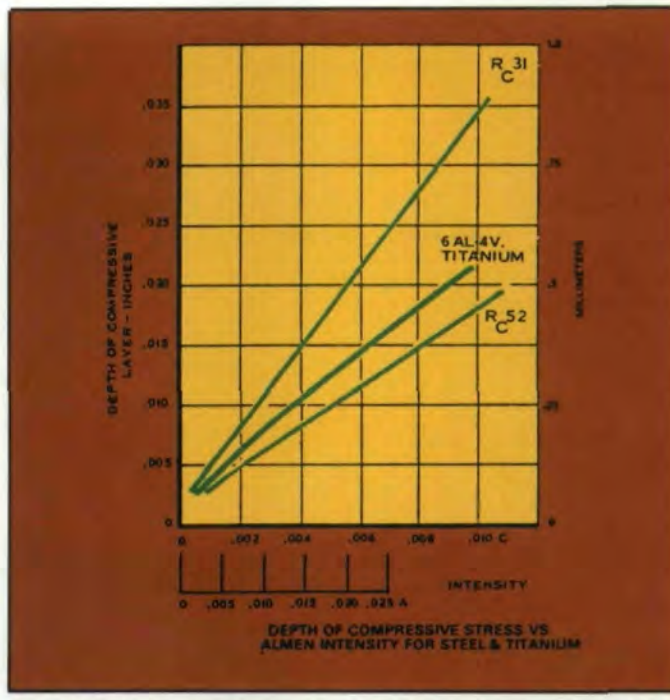

Fig. 5—Depth of compressive stress vs Almen intensity for steel and titanium.(4)

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.

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 Mil Spec 13165B Amendment II.(3) Note in Fig. 5 that as the hardness of the work piece increases, the depth of the 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 factors are wear, general erosion, if any, possibility of 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 10% 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. These are a function of the ultimate tensile strength of the material being peened and generally are in the range of 50% to 60% of the ultimate tensile strength (UTS) cuts of the base material. A tensile load level maximum is generally accepted to be 40% to 50% 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.

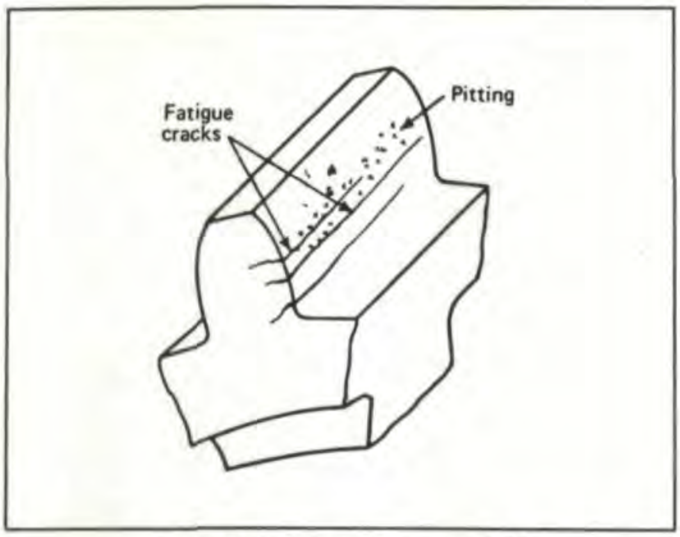

Fig. 6—Typical pits and fatigue cracks[7]

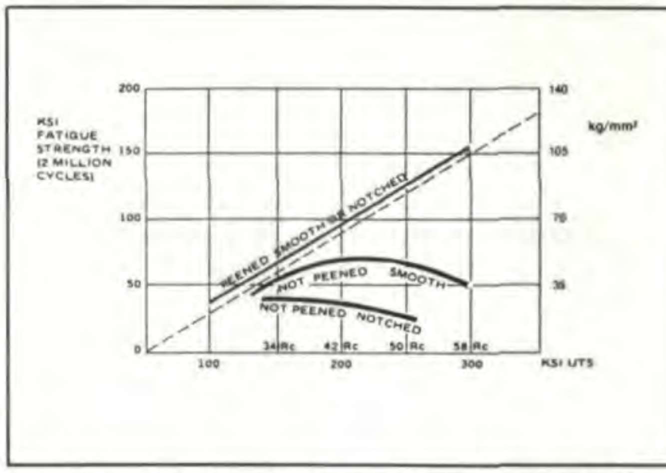

Fig. 7—Comparison of peened and unpeened fatigue limits for smooth and notched specimens as a function of ultimate tensile strength of steel.

2. Increased surface fatigue life to reduce pitting and increase durability (See Fig. 6).

Another benefit accruing from shot peening gears is improved lubrication of the gear by virtue of the many small reservoirs (dimples) that can store lubricant at the point where it is most needed; thus, negating the squeegee effect of the 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 or 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).

As hardness increases, the reduction in fatigue strength in both notched and unnotched unpeened steel specimens 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. 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 30% improvement in fatigue limit. A 33% increase on induction hardened 4140 material is reported. The same authors also stated that nitrided steel surface tests showed moderate results[8].

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

Of course, proper selection of shot size and hardness is an important consideration. 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).

Townsend and Zaretsky stated that shot peening produces residual subsurface 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% for the shot peened gears over the standard gears at a depth of maximum shear stress in addition to a 350% increase at a depth of 0.5 mil. Further, there was an increase in surface pitting fatigue of 1.6 times that of non-shot peened gears[9].

As a result of the growth in confidence in the shot peening process, Lloyd's Register of Shipping[10] allows an increase of tooth loading for both wear and strength of up to 20% 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

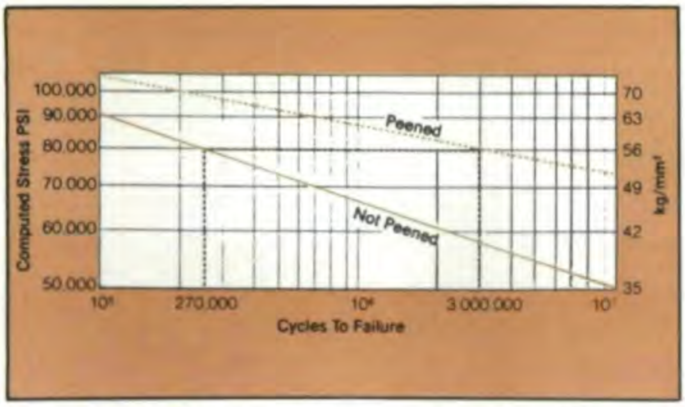

Fig. 8 – Effect of shot peening on carburized gears.[4]

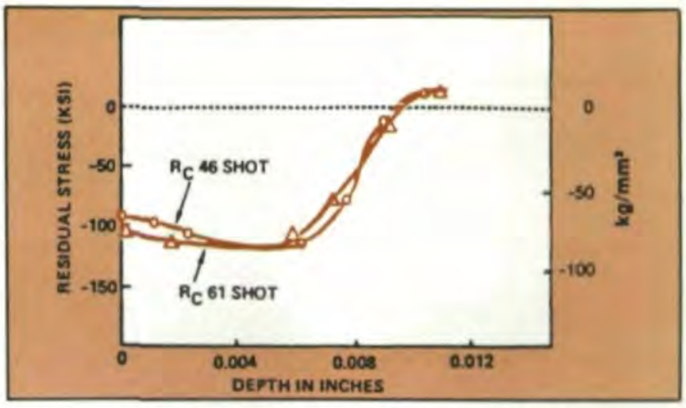

Fig. 9 – Peening 1045 steel at RC 48 with 330 shot.

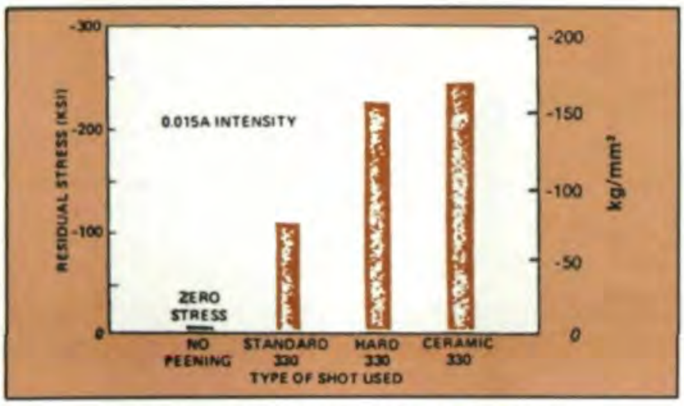

Fig. 10 – Peening 1045 steel at RC 62 with 330 shot.

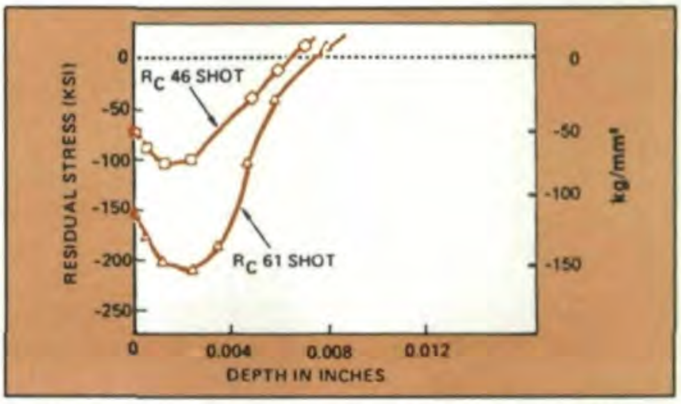

Fig. 11 – Residual stresses induced on 300M using various shot.

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, the Almen strip measures intensity for a given set of conditions of shot size, shot velocity, shot hardness and angle of impingement.[3] MIL-S-13165B also gives specifications for both steel and glass shot, which cover screening tolerances of new shot by size, set limits on hardness where applicable, specify uniformity of shot in the machine and set standards for shape with allowable deviations.

Shot quality *is important* to successful peening and must be continuously monitored. Vigilance is especially necessary on those machine installations where a single size shot is run continuously. The temptation to add make up shot whenever reduced flow is noted without checking, screening and sizing the old shot seems to be irresistable 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 will slowly 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 (See Fig. 12). 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 have 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 of getting at least 100% coverage on all of the part during manufacture, a sad commentary on the 10X glass as an inspection tool. The borescope (See Fig. 12A) while allowing examination of cavities and holes, suffers from the same limitations of limited field and mobility in contoured areas.

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 not permitting 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.

Now there 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 dur-

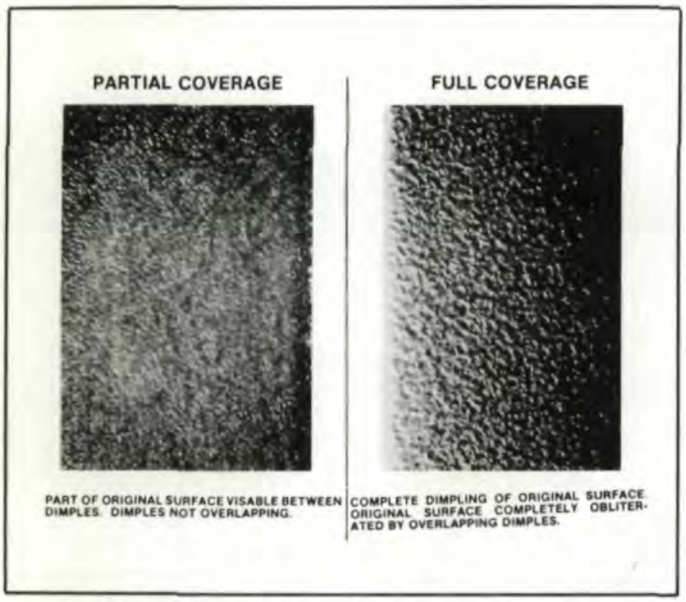

Fig. 12—Partial and complete shot peening coverage.

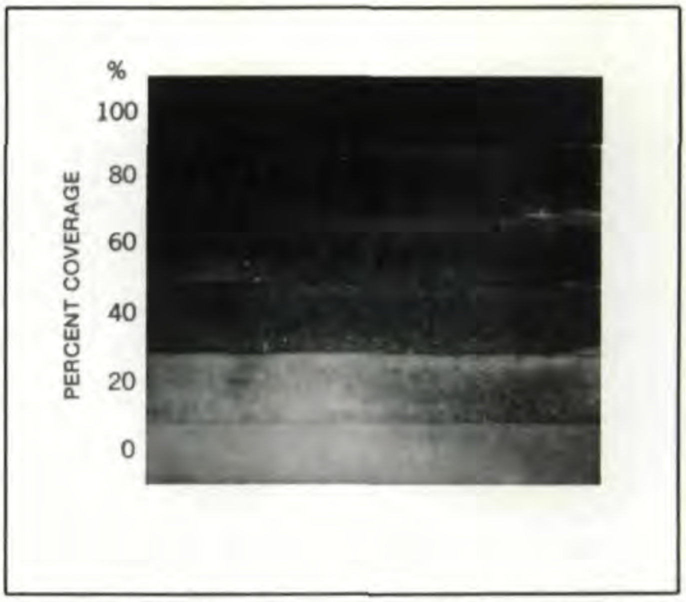

Fig. 13—Varying degrees of coverage shown by Peenscan process.[4]

ing 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. 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, areas improperly peened will show evidence of some material remaining as a white shadow of varying intensity, depending upon the degree of coverage actually obtained. See Fig. 13. 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-S13165B[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 the industry has had automatic equipment for a number of years, the shot peening operators have never satisfied most gear manufacturers on the inability 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 aborted 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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Fig. 12a (Left)—Examination of helicopter hub assembly with a boroscope.

IMPROVED GEAR LIFE . . .

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PRACTICAL ANALYSIS OF HIGHLY LOADED . . .

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Conclusion

Based on the DIN/ISO formulae for scoring capacity, a simplified method adopting a modified scoring index has been developed. As can be seen from typical applications, this method works with sufficient accuracy.

The calculation of scoring capacity will become more and more important in parallel with an increasing demand in transmitted power per gear volume. The practical experience with highly-loaded gears with regard to scoring will give more safety in the application of this calculation method and will possibly permit a reduction of the safety margins used today.

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GEARS FOR NONPARALLEL SHAFTS . . .

(continued from page 62)

sacrificed to obtain a large mechanical advantage. Typical applications are standby pumps, large valves, and gates.

2. *Intermittent, manual* operations requiring a *large mechanical advantage*, such as in steering mechanisms and opening and closing of valves and gates by means of handwheels (Fig. 14).
3. *Motorized, nearly continuous* operations where worm gearing competes with gear reduction units. When space is at a premium, as in machine tools, packaged, motor-driven worm reduction units are used in preference to gear reducers (Fig. 13). Depending on size and application, the unit may be self-contained or built integrally with an electric motor. Because of silent operation, such units are preferred in machine tools and also in elevators. These units all require multithreaded worms and ratios not exceeding 1:18. Larger ratios are achieved by connecting two units in series.

Design Detail of Worm Gearing

The unit shown in Fig. 15 is a typical, medium-size worm gear speed reducer. Smaller units of this type usually have housings of cast aluminum alloys for maximum thermal rating. For larger units the preferred material is cast iron. The worm is case-hardened and ground alloy steel of integral shaft design. The gear is cast bronze with generated teeth and keyed to the output shaft. Larger worm gears are often composed of a ring of bronze mounted on a center or hub of less expensive material. A common design utilizes a flanged rim mounted on the hub by means of shear bolts (Fig. 16*a*). Equally common is mounting by means of a press fit (Fig. 16*b*) assisted by a pin connection. The output shaft is high-quality, medium-carbon steel, ground to close tolerances. The worms and output shafts are frequently mounted on roller bearings. All shaft extensions are equipped with lip style, synthetic oil seals.

Lubrication

Generally, oil is contained within the housing and directed by splash to the bearings and to the zone of tooth and thread contact. Natural splash may be augmented by flingers, scrapers, and cups attached to the gear. Channels or ribs may be furnished inside the housing to help direct oil to the bearings.

Summary

Despite higher initial cost, gears for nonparallel shafts are justified because they often save space and lead to a better design. Kinematically, these gears all perform the very difficult task of changing the plane of rotation. With the exception of crossed helical gears, all have reached a high degree of perfection and a long, useful life of transmitting power. Hypoid gears for automotive differentials, for instance, rarely fail during the life of a car. The versatility of worm gearing is due to the inverse relationship of efficiency to torque and reduction ratio. Table 1 summarizes comparative characteristics of speed reducer gear families.

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