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SHOT PEENING

IN

THE DESIGN OF GEARS

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INTRODUCTION

Shot peening is a process which might well be considered in the design of any machine part which is required to carry high loads with a minimum size or weight of the overall unit.

This paper represents an attempt to show that shot peening can be used effectively not only to eliminate fatigue failures, but also in design, to increase load carrying capacity per pound of gears as well as other machine parts.

Naturally, any pair of gears designed for high load carrying capacity involves good manufacturing practice with respect to the geometry of the gears, material, manufacture and metallurgy. As in any other machine part, the impovement by virtue of shot peening will start from the level of quality of the gears without the benefit of shot peening.

A few years ago, shot peening of a particular machine part may have been looked upon as evidence that the part in question had at some time given trouble in service by reason of fatigue failures. Today shot peening is being considered more and more as a means of increasing the allowable fatigue strength in the design of machine parts. The fact that a part is being peened in production does not necessarily imply that fatigue failures have been experienced on that part in the field.

WHAT IS SHOT PEENING?

Shot peening is sufficiently well known that it is necessary only to define it briefly as a process utilizing the impact of metallic shot for the purpose of setting up a layer of compressive stress in the surface of a metal part. This compressive stress in the surface is very effective in increasing the fatigue strength of that part. Control of the process is discussed in a later section of this paper.

PRODUCTION PEENING — CURRENT EXAMPLES

The type of machine parts to which shot peening is applied in production for increasing life or load carrying capacity extend all the way from small springs to locomotive bull gears, and include almost every conceivable type of spring; axle shafts, torsion bars, propeller shafts, crank shafts; connecting rods and other engine parts; chain links, universal joints; spur, helical, and bevel gears; steering knuckles and almost every type of part in which fatigue failure is recognized to be a problem. Materials peened include steel of various hardnesses, iron, aluminum and aluminum alloys, brass, bronze and magnesium.

There are many instances in which gears of various types are peened in regular production. Practically all of the major automobile manufacturers use gears and other machine parts which are peened in regular production. The aircraft industry uses shot peening quite extensively.

A very interesting example of the adoption of shot peening in heavy duty truck transmissions was reported by Mr. T. Backus, Vice President in Charge of Engineering at Fuller Manufacturing Company in Kalamazoo, Michigan. The following is an excerpt from his paper. (1)*

> Several years ago, heavy duty trucks were put into service hauling iron ore from open pit mines in Minnesota. These trucks were heavily loaded and were then required to climb a long 8% grade, always in the same gear ratio, from the bottom of the pit to the top. Under these stepped-up conditions, the transmission gears were overloaded to the extent that premature failures occurred. After trying coarser pitch gears and improving fillets at the roots of the teeth without success, shot peening was considered as a possible remedy. Tests on the dynamometer showed that these gears when shot peened had no failures at a life of 5 times the average of the same gears non-peened.
>
> As a result of these tests, a group of peened gears was sent to the mines for a field test. The improvement in fatigue life was sufficient to eliminate the trouble in this transmission. The results confirmed the laboratory tests.

TORQUE CONVERTER IN A WELL KNOWN TRACTOR

Under very severe conditions when using a tractor for bulldozing, the very sudden changes in speed and load called for a compact two speed auxiliary transmission. However, due to space limitations in the vehicle it appeared impractical to install an auxiliary transmission which was sufficiently large to take the required torque. In this case shot peening provided the additional fatigue strength for a commercially satisfactory result. These are only a few of the many field applications where shot peening has proved invaluable.

In running laboratory tests to determine life before pitting Mr. Backus always shot peens the gears in order to eliminate any danger of tooth breakage during the test on pitting.

In addition to improving the fatigue life, shot peening is commonly used to improve bearing qualities by providing oil reservoirs in the dents produced by shot peening. In some cases this improvement has been sufficient to eliminate the bushing under some gears and replace tin plating in other instances. This practice has been followed on some parts for several years, with uniformly successful results.

The International Harvester Company reports that by peening they were able to increase the load 27% and still obtain an improvement of 56% in the fatigue life on small steering knuckles. On a larger knuckle an increase of 21% in load was made on the peened knuckles and the life was still 121% longer than in the non-peened knuckle. Similar results on transmission gears have made it possible to in-

*See Bibliography.

crease the load on dynamometer tests from 225 to 260 foot pounds of torque, (or an increase of 15%) and still obtain 50% longer fatigue life.

SHOT PEENING AS A DESIGN FACTOR

There are a large number of applications in which the addition of shot peening to a given design has permitted the successful continuance of that design in production, in spite of greatly increased load carrying requirements. This seems to clearly illustrate the adaptability of the same process for use in the original design of machine parts in which the advantage of increased fatigue strength can be realized.

HOW MUCH INCREASE IN FATIGUE STRENGTH?

When shot peening is considered in the design of a pair of gears, one of the first questions which arise is "How much increase in the allowable bending stress can be obtained by the process?" This is not a constant value, but depends upon the order of magnitude of the working stresses involved. Or, to put it another way, it will depend upon the required useful life of the gears at maximum load. Figure 1 shows an SN diagram

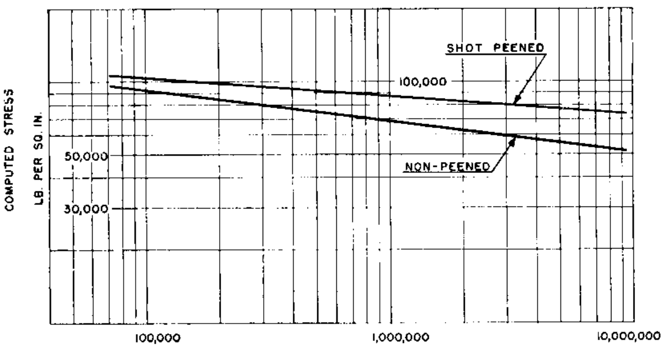


Figure 1 — Fatigue Chart of Carburized Automotive Type Spur and Helical Gears, Shot Peened and Non-Peened

for carburized and hardened automotive type spur and helical gears. (2) The lower line shows the relationship between computed bending stress and average life for non-peened gears, and the upper line, for shot peened gears. It will be observed that these lines tend to converge at the left of the chart where the stress is high and the life correspondingly short. Actually, if the two lines were projected to the left, that is toward the region of static failures, the two lines would intersect. In other words, shot peening is not effective in increasing the static strength of the material, but becomes increasingly effective as the required useful life is increased. Referring to the chart, at a life of 100,000 cycles the increase in allowable stress due to peening is about 10%. However, at a required life of 1,000,000 cycles, the increase in allowable stress is a little more than 25%. Proceeding still further to the right, at a required life of 10 million cycles, the increase in allowable stress is close to 50%.

It should be emphasized that the figures just quoted represent the increase in *allowable stress* for a given life as distinguished from increase in life at a given stress. The increase in life at a given stress is much greater. For example at a stress of 80,000 lbs/sq. in. the increase in average life resulting from shot peening is approximately 1000%.

It should be further emphasized that the chart shown in Figure 1 does not represent the optimum that can be obtained by shot peening, but is representative of an average job with no attempt to achieve the best possible results.

It would be a difficult matter to enumerate all of the applications in which shot peening could be used effectively in the design of machine parts, but a few examples of such applications could be cited as follows:

1. A machine part may be required to fit into a limited space for proper operation. In such cases, the capacity of the machine may be limited by the fatigue strength of a spring or other part which cannot exceed a given size. An example would be a pair of gears in which a given center distance cannot be exceeded because of other considerations in the overall design.
2. In some cases it is highly desirable to decrease the weight of a machine part to a minimum for better functioning of the machine. An example of such an application is the chassis spring of an automobile. In this case, at least part of the spring can be considered as unsprung weight which should be a minimum for good riding qualities. Other examples include aircraft parts, in which weight should be at a safe minimum.
3. Probably one of the most attractive applications for shot peening in design is that in which machine parts can be made smaller and lighter for more effective utilization of material. This application is usually associated with parts made in high volume production. The incentive in this case is the decrease in cost of production without sacrificing quality.

   An example of the possibility of saving weight as a means of reducing production costs can be taken from an application in which coil chassis springs have been peened in regular production for several years. Based on the regular production schedule, and using actual production cost figures, a very conservative estimate was made assuming an increase in allowable stress of 10%. In order to be ultra conservative, it was assumed that this increase in stress would allow an equal decrease in weight. This assumes a decrease in wire diameter only, and the necessary decrease in length to obtain the same spring rate was neglected. After allowing for all direct labor and the total cost of operation and maintenance of the equipment, a net saving in material of $25.00 per hour of operation of the peening machine was estimated. Actually, according to stress formulas used in the spring industry an increase of 10% in allowable stress results in a saving of 20% in weight and space. On this basis, the net saving in this application would be more than $50.00 per hour of operation of the peening machine. It should be further mentioned that in this estimate, the cost of spring steel was assumed at the ultra conservative figure of 5 cents per pound. But even on the basis of these conservative figures this would amount to a saving of $350 per shift of 7 hours.

The above estimate was made not on the basis of a goal to shoot for, but a conservative comparison on the basis of what is now being done. The assumption of a 10% increase in allowable stress is comparable to what we would expect for a very short life requirement. With longer life requirements the allowable stress increase by shot peening would be materially greater.

A striking example of shot peening in the design of leaf springs was reported by Spring Perch Company. (3) In a leaf spring assembly which had previously contained 7 leaves, the number of leaves had been reduced to three, thus effecting a saving of 30% of the total weight of the spring assembly. This was not a case of conventional peening, but rather one of stress peening, which involves peening the leaves while they are subjected to a stress in the same sense as that applied in service. No estimate was made of the saving in dollars and cents, but very little imagination is necessary to visualize the reduction in cost of material in volume production.

GEAR DESIGN

BENDING STRENGTH

It will be noted that the above comparisons on springs involve stresses which are applied to the major portion of the spring, as distinguished from cases in which the maximum stress occurs only in highly localized areas. In the case of highly localized stresses such as occur in the fillet or junction between different cross sections, the saving in weight may not be appreciable. Each case must be treated in the light of its own requirements.

However, this does not mean that all cases of localized stresses are to be excluded from the types of parts with which an attractive reduction in production cost can be accomplished. For example, in gears which are subject to fatigue failure due to bending stress, the maximum stresses are located at the tooth fillets. It might appear at first glance that the possibilities of reducing weight by shot peening are meager. This is not necessarily the case. For gears of similar geometry, the maximum bending stress in the tooth fillet will vary inversely as about the cube of the pitch diameter, or the cube of the center distance. A decrease in center distance, of course means that the size of the entire housing can be decreased in proportion.

The weight of a spur or helical transmission will vary approximately as the cube of the center distance, other conditions being constant. This means that, in cases where bending strength is the controlling factor, if the allowable bending stress is increased, the weight of the unit can be reduced in the same proportion.

For example, if the required life under maximum load conditions is in the neighborhood of 100,000 cycles, by referring to Figure 1, it can be seen that the allowable stress can be increased by 10%. This would result in a decrease of 10% in the weight of the entire unit. For a required life of one million cycles at maximum load, the increase in allowable stress is 25% which would result in a decrease of 25% in the weight of the assembly. These estimates of course are based upon the assumption that other parts in the assembly are not so critical that the potential reduction in size of the unit is limited by such members. For example, if the size of the unit is decreased to the extent that it does not permit space for a bearing of adequate capacity, then that bearing would establish the limit of reduction in the size of the unit.

SCORING

The fact that shot peening is most commonly used as a means of increasing fatigue strength in bending or torsion does not mean that the process should be ignored in a gear design which may be subject to scoring. The data available indicate that shot peening has little direct influence on scoring or pitting. However, when we consider the overall design of a pair of gears, it will be recognized that bending strength sometimes conflicts with scoring resistance. For example, a coarse pitch is favorable for bending strength because of the greater thickness at the root of the tooth. However, due to the greater tooth height necessary for adequate tooth contact ratio, (assuming the same pressure angle) tooth action will take place closer to the base circle, with a consequent decrease in the radius of curvature. This results in a higher compressive stress both at the beginning (or end) of action, and at the highest point of single tooth contact. Also, due to the greater tooth height as well as greater normal pitch, the sliding velocity will be greater with a coarse pitch than with a fine pitch.

This leads to the conclusion that although a coarse pitch is favorable for bending strength, a fine pitch is favorable for scoring resistance. But if shot peening is considered in the design of the gears, it can be used to permit the use of a finer pitch for greater scoring resistance by providing the necessary increase in bending strength. Carrying this concept somewhat further, shot peening may be used to accomplish a decrease in size of the gears, even though the application may be more vulnerable to scoring than to bending failures, provided the design with peening is balanced for equal resistance to scoring and bending failures.

PITTING

In cases of high ratio gears in which tooth action approaches the base circle of the pinion, the compressive stress might be very high because of the small radius of curvature in that region. This naturally suggests the use of long and short addendums, but even then the high compressive stress might present a problem. This condition again suggests the use of a finer pitch, which in the case of very high ratios may not permit a further decrease in the gear addendum, but it would permit a greater contact ratio for better distribution of the transmitted load. In more moderate ratios, in which pitting is more likely to occur just below the pitch line of the pinion, the benefit of a finer pitch would probably be less than in the case of high ratios, although it would result in a slight increase in contact ratio for full depth teeth.

GEAR NOISE

The question sometimes arises whether there is a sufficient dimensional change due to peening to introduce errors in gear tooth profile. With proper peening procedure, there should be no significant change in profile, particularly in hardened gears. Some manufacturers have compared the noise level of peened gears against identical gears non-peened, and were unable to detect any difference in the noise level. At least one manufacturer insists that shot peened gears are more quiet in operation than the same gears non-peened. Both of the cases cited above are related to carburized and hardened gears.

In most cases of shot peening in production of gears, peening is the last operation insofar as the teeth are concerned, and no attempt is made to protect the tooth profiles from the blast. However in some cases the gears are cut with a protuberance hob to provide an undercut at the roots of the teeth. The gears are then hardened, shot peened and ground. In large gears, this procedure allows the tooth profiles to be ground without removing any of the shot peened surface in the fillet where the bending stress is maximum. This provides a means of overcoming distortion in heat treatment, and also a ground profile where this is considered essential.

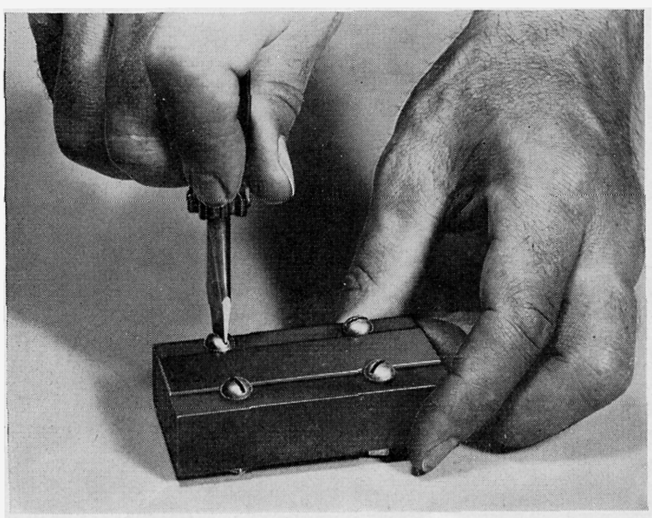


Figure 2 — Fastening Almen Test Strip to Holder

CONTROL OF SHOT PEENING

Shot peening is controlled by means of a standard Almen test strip of spring steel which is subjected to the peening blast in the same program as the work, and then measured for the degree of curvature resulting from the blast. A standard test strip holder is used for holding the strip during the peening cycle. Figure 2 shows a test strip being fastened to the holder preparatory to the peening cycle. Figure 3 shows the two standard

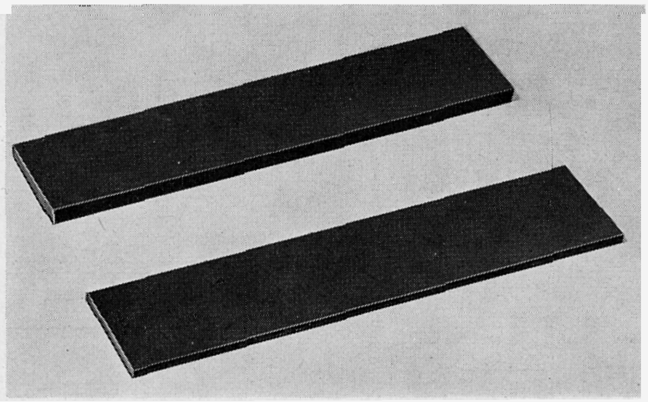


Figure 3 - Standard Almen "C" Strip (above) and "A" Strip (below)

types of test strips. The A strip has a specified thickness of .051" and is used for peening jobs involving moderate impact. The C strip has a thickness of .0938" and is used for heavy impact values. Figure 4 illustrates a non-peened A strip at the

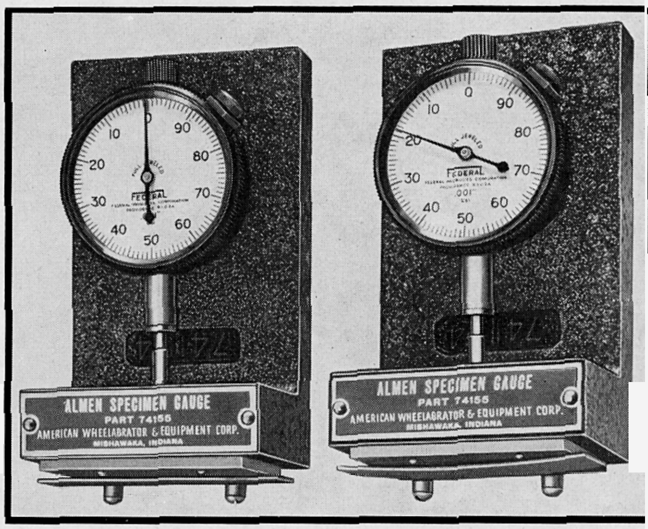


Figure 4 — Almen Specimen Gage for Measuring Arc Height of Almen Test Strips

left, and a peened A strip at the right, being measured on a standard Almen gauge. The gauge measures the combined height of arc both longitudinally and transversely on the strip as it is placed with the non-peened side toward the dial indicator. The peened strip in Figure 4 would be referred to as having an arc height of .019 A.

This measuring equipment is used to control the peening operation after the peening specifications have been set up. Any change in the peening cycle will be reflected as a change in the arc height as measured.

In setting up a peening job, it is necessary to specify the peening requirements on the basis of full sized shot if efficient operation is to be obtained. Any broken shot which is allowed to remain in the machine is completely ineffective in increasing fatigue strength beyond that which is obtained with the full sized shot alone.

For example, assume a part to be peened with full sized shot for a duration of exposure only sufficent to produce 30% coverage and an arc height of .011 A. Now, consider an identical part peened with the same quantity of full sized shot together with a much larger quantity of definitely undersized shot so that the resulting coverage would be complete and the arc height increased to .014 A. Fatigue tests have indicated that even though the arc height and coverage were appreciably greater in the second case, the increase in fatigue strength of these two parts would be practically the same. However, if complete coverage had been obtained with the full sized shot, at a reduced shot velocity, to produce an arc height of .014 A, the fatigue strength would have definitely exceeded that of the above example. These data illustrate that arc height of itself is not a criterion of the quality of a peening job in the absolute sense. It is intended as a means of maintaining constant conditions in a peening machine and is quite valid for that purpose.

It is evident from the foregoing discussion that for efficient operation, a peening machine should be equipped with a separator capable of removing broken or undersized shot in continuous operation. Of equal importance is the provision for uniform replacement of the broken shot with new shot.

In cases where blast cleaning is done in the same plant, it is quite practical to use the broken or undersized shot in the cleaning machine, provided it is of the proper size for the cleaning job.

For efficient operation it is also important that the shot strike the work as nearly as possible at right angles to the surface in the region of maximum stress in service. Any shot which strikes the work at an angle appreciably less than 90° is ineffective in the same way as undersized shot.

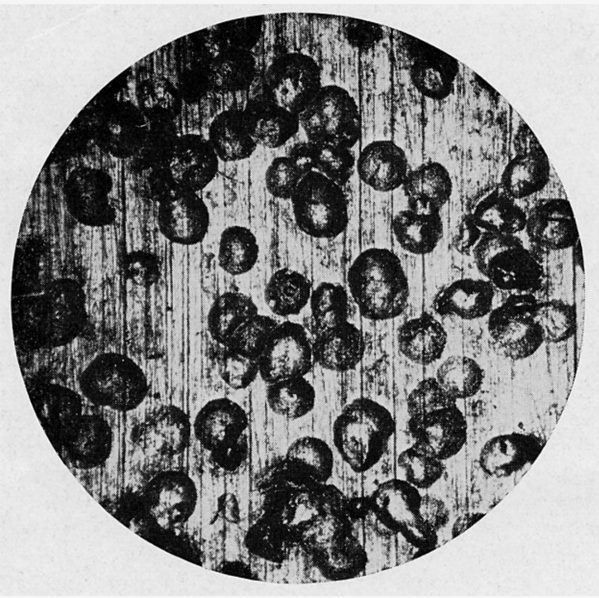
ARC HEIGHT

In setting up specifications for shot peening, the arc height should be established in relation to the thickness of the part at the location of maximum stress, and the overall requirements of the particular job. It is not feasible to set down a hard fast rule for arc height, because of widely varying requirements. Wherever possible, it is good practice to establish, by fatigue tests on shot peened parts, the range of arc height most suitable for the particular application. However, the following tabulation can be used as a rough guide:

Thickness of Part	Arc Height
1/16	.004 A
1/8	.008 A
1/4	.014 A
3/8	.018 A
1/2	.021 A
5/8	.007 C
3/4	.008 C
7/8 or greater	.010 C

COVERAGE

For efficient operation, coverage should also be considered in relation to the requirements of the job. Coverage may be defined as the proportion of a given area of the work which has received direct impact of the peening blast. The photograph on the left in Figure 5 shows a polished Almen test strip which has been peened to a coverage of 55%. That is, the area of the indented portion represents 55% of the area of the photo-



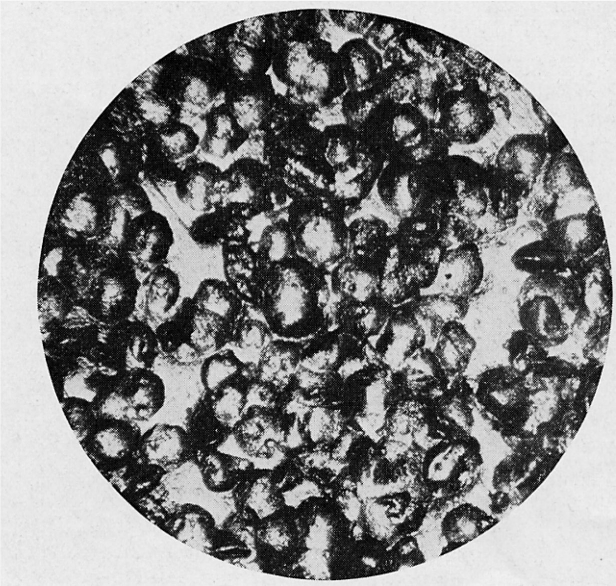


Figure 5 — Photographs Showing Coverage on Polished Almen "A" Strips: 1 pass - 55% coverage — 3 passes - 90% coverage

graph, as measured with a planimeter. The photograph on the right shows a similar strip with 90% coverage. (4).

In any peening operation in which conditions are constant there is a definite relationship between coverage and exposure time, as shown in Figure 6. The horizontal scale is relative, and can be expressed in terms of time or number of passes under given conditions.

As shown in Figure 6, coverage is obtained relatively fast at the beginning, but as it approaches 100% the rate of increase in coverage becomes progressively lower.

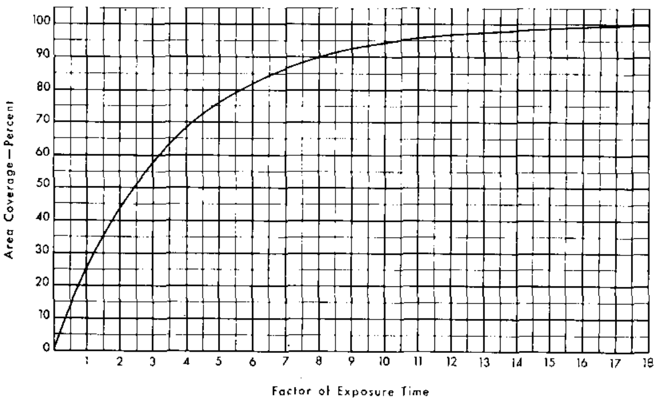


Figure 6 — Relationship between Area of Coverage and Exposure Time

Theoretically, coverage approaches 100% as a limit as the exposure time is increased indefinitely. Note that the exposure required to obtain 98% coverage is about 2½ times that required to obtain 80% coverage.

INFLUENCE OF COVERAGE ON FATIGUE STRENGTH

The relationship of exposure time and coverage cited above naturally raises the question as to the influence of coverage on fatigue strength. Fatigue tests have indicated that a coverage of 98% results in an increase in fatigue strength above that for 80% but not in proportion to the additional exposure time. Because of the fact that the coverage approaches 100% as a limit, it is reasonable to believe that additional life can be obtained by prolonged exposure after a coverage of 98% is obtained. This is supported by fatigue data which show a gradual increase in life with increased coverage well beyond that at which there are no visible areas which have not been indented. It should be mentioned, however, that the data are based on coverage at the same arc height, which is not excessive for the thickness of the part. If the arc height is excessive, a point of diminishing returns may be reached, at which the gain in fatigue strength will be less than at a lower arc height. A greater degree of coverage can be obtained at a given arc height by increasing the exposure time at a lower shot velocity. This suggests that the type of peening, or more specifically the degree of coverage most suited to a particular application will depend to a large degree on the economic factors involved in the manufacture of the part. For example, in the production of a large volume of small and relatively low cost parts, a coverage of 80% may be adequate to yield a sufficient increase in allowable stress to provide a substantial saving of material, and the rate of production would be more than double that obtained with a required coverage of 98%.

At the other extreme, a part might be considered which is inherently expensive to the extent that the exposure time involved in the production of that part is of little consequence in the overall picture. In such a case, it may be economical to provide sufficient coverage to obtain the maximum benefit from the shot peening operation. This may be several times that exposure required for 80% or even 98% coverage.

The actual production rate varies considerably in different applications, but a typical case would be gears rotating on an arbor and passing directly through the blast. In a Wheelabrator type of peening machine a conveyor speed on the order of 10 to 15 ft/min. or more is commonly used on gears with a pitch diameter in the neighborhood of 3 or 4". In the case of very large gears, the conveyor speed might be as low as 2 ft/min.

CHOICE OF SHOT SIZE

The choice of shot size for a peening operation will depend upon the arc height and coverage required in the particular application, with due consideration for sharp corners or fillets. (The usual rule in this case is that the nominal diameter of the shot should not exceed the radius of the fillet.) Fatigue tests have indicated that for a given coverage and arc height, other conditions being the same, the same increase in fatigue strength can be obtained with one shot size as with another, with due consideration to shot velocity.

Since the number of pellets per pound of shot varies inversely as the cube of the diameter of the particles, it is only natural that coverage is obtained at a much higher rate with smaller shot. This of course implies that in order to obtain the same arc height with the smaller shot, it is necessary to increase the shot velocity. However, in spite of the fact that the rate of shot usage increases rapidly with shot velocity, the increased production resulting at the higher conveyor speed compensates for the rate of shot usage so that the shot usage per unit of production is approximately the same. The net result is that with the smaller shot higher production rates are obtained with no increase in cost of operation.

TYPE OF SHOT

For several years, it was considered necessary that the hardness of the shot should be at least equal to that of the work being peened. Under these conditions, chilled iron was the only type of shot used for peening fully hardened work. Since the advent of steel shot however, fatigue tests have shown an equal increase in life for fully hardened parts (60 Rockwell C) when peened with chilled iron shot and with steel shot having a hardness in the neighborhood of 45 Rockwell C. This

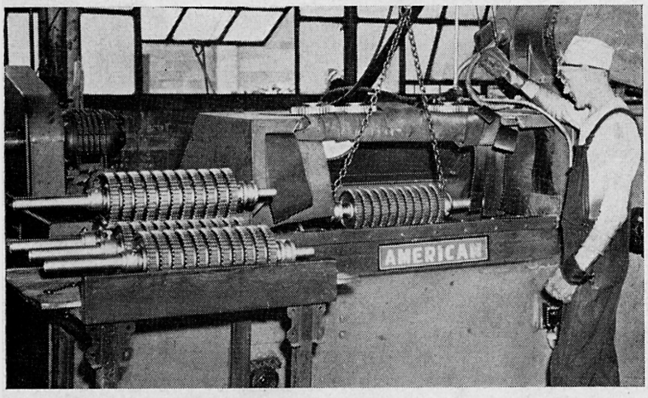


Figure 7 — Production Peening of Transmission Gears

is a distinct advantage because the rate of usage with a good quality steel shot is a fraction of that with chilled iron shot. It is important, however, that the hardness of steel shot is not appreciably less than 45 Rockwell C. Any shot which is appreciably softer is ineffective in the same sense as broken shot. Even for work with a hardness of 40 to 45 Rockwell C, a wide range of hardness in the shot results in an inefficient blast because the softer particles do not add to the work done by the harder particles.

TYPES OF EQUIPMENT FOR SHOT PEENING

For uniform results, the work should pass through the blast in a mechanically controlled cycle to insure that all surfaces subject to high repetitive stresses are uniformly covered by the blast. For low volume of production, or in some particular cases where only a small area of a relatively large part is to be peened, an air blast might be sufficient. However, for high rates of production the airless method involving a rotating bladed wheel is more practical and economical. Figure 7 shows the loading of transmission gears into a Wheelabrator airless peening machine. Figure 8 shows a similar machine for peening bevel gears and pinions.

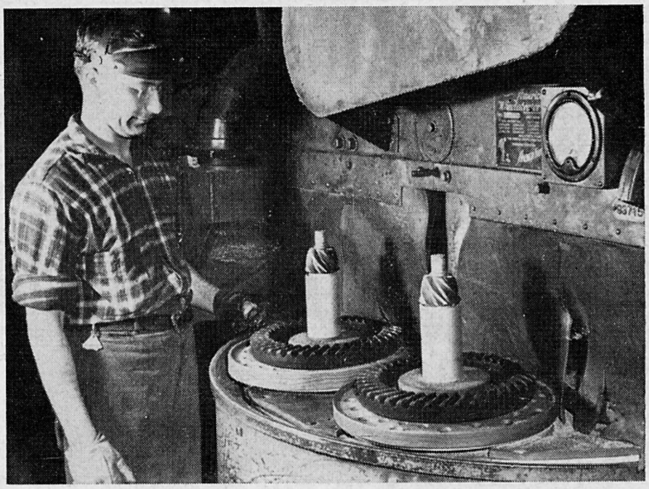


Figure 8 — Production Peening of Bevel Gears

BIBLIOGRAPHY

1. "Shot Peening of Heavy Duty Transmission Gearing" by T. Backus. Paper presented at a meeting of Division XX of the SAE Iron and Steel Technical Committee, September 21, 1951.

2. Progress Report by Automotive Gearing Committee AGMA 101.02, October 20, 1950.

3. "Three Leaf Automobile Spring at Less Cost" by A. H. Allen, Steel, March 20, 1950.

4. "Shot Peening", published by Wheelabrator Corporation, Mishawaka, Indiana, 1951.