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Special Performance of Transmission Parts by Shot Peening

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AFTER MORE than a quarter of a century of use as a production process, shot peening is today one of the most effective means of preventing premature fatigue failure.

Its applicability for this purpose is demonstrated by the many thousands of automotive parts, such as transmission and rear axle gears, axle shafts, valve springs, chassis springs, etc., being peened in regular production. But its use as a factor in the design of components is far short of its real capability.

Shot peening involves the impact of shot on the surface of the work to be treated. This results in a residual compressive stress in the surface. An attempt will be made to clarify the influence of the residual stress distribution on the results obtained. It is likely that when the significance of the residual stress distribution is fully understood, and means of improving it are found, the process will take on a new look, with fatigue strength beyond anything that is visualized today. This discussion deals not with the possible achievements that might be made, but rather with a process that is now available on a practicable basis.

Some fundamental aspects are discussed, and results on gears are given, as well as those on laboratory fatigue specimens, to support the theories presented.

Some suggestions are given in the hope that more effective utilization of the process might be obtained in existing production operations, either by improving the gain in fatigue strength or by reducing cost.

BENDING FATIGUE STRENGTH

One of the most common problems in the drivetrain of a vehicle is that of fatigue strength. Coincidentally, that is the region in which data are most available with respect to the gain afforded by shot peening.

In determining whether it is applicable to a given problem, the question arises, "How much gain in fatigue strength is available?" It is necessary to recognize that we are dealing with a fatigue problem, and it is a complex one to answer on a quantitative basis.

The degree of increase is subject to a number of variables, including the magnitude of applied stress, stress range, life requirements, surface conditions existing in current production, if any, the material in the component to be peened, notch sensitivity, etc., to say nothing about the influence of the peening conditions themselves. Due to these variables, it becomes apparent that any answer is necessarily qualitative. Even on a qualitative basis, we must first define the terms involved in a comparison. It is quite common to compare the life to failure when a part is subjected to a common cycle of

ABSTRACT

The purpose of this paper is to illustrate the value of shot peening in reducing production costs where high volume is concerned. Its potential as a means of reducing part size via increased fatigue strength can result in saving material to the extent of hundreds of dollars per day.

The significance of the distribution of residual stresses within the shot-peened part is discussed, and theories are presented in an attempt to explain some of the startling effects of shot peening.

The economics of efficient operation of peening equipment are discussed, and suggestions are given to minimize operational costs.

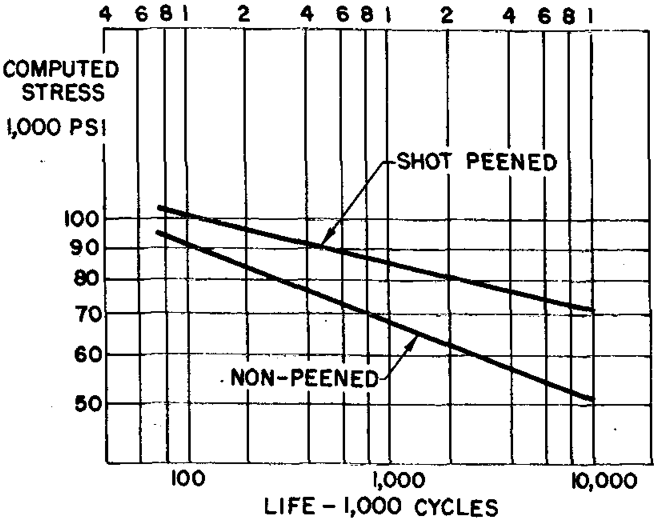

Fig. 1 - Fatigue chart of carburized automotive type gears, shot peened and nonpeened (simple bending)

Table 1 - Testing of Marine Gears

Applied Stress (Relative), %	Life Cycles to Failure Nonpeened, Failed	(Simple Bending) Peened, Not Failed
100	900,000	1,000,000
120	–	1,000,000
140	–	1,000,000
160	–	1,000,000

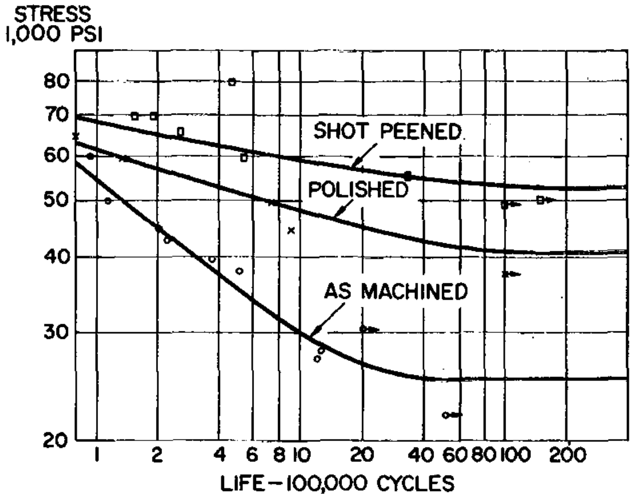

Fig. 2 - Fatigue chart of flat laboratory specimens SAE 4340 steel, 23 Rc (reverse bending)

applied stress. In such a comparison, a peened part may be expected to last many times the number of stress cycles an identical nonpeened part can endure. The corresponding gain for the same application, but in terms of allowable stress for a given number of cycles to failure, will be a much lower ratio. For example, a gain of only 20% in stress for a given number of cycles could be equivalent to 1000% or more in life for a given stress.

Fig. 1 shows a fatigue chart on logarithmic scales for comparison. The lower line shows nonpeened helical gears, and the upper line shows similar gears peened. These are of the automotive type, carburized and hardened, subjected to conventional service in which the applied stress cycle is from zero to maximum. This chart has been derived on the basis of a large number of tests over a number of years.

Note that the two lines diverge with increasing numbers of cycles, or with correspondingly lower stresses.

Fig. 1 is not intended to indicate the potential possibilities of the process under ideal conditions. Rather, it is a compilation of a variety of gears, peened under various conditions, and therefore represents somewhat of an average for a number of variables.

To cover all of the considerations involved in such a comparison is beyond the scope of this discussion, but it is probably safe to say that, in the majority of cases, even under unfavorable conditions, a gain of 10% in allowable stress would be a very conservative estimate for automotive gearing.

A specific example of much greater gain in the fatigue strength of gears is one in which marine gears were tested on a dynamometer. These were large, double helical gears with a normal diametral pitch of 4.0 and a hardness of 40 Rc. The peening was done at an arc height of 0.011 A and a coverage of 7.0. (This will be defined in a later paragraph.)

The results of these tests are shown in Table 1. This test was discontinued after the application of 160% stress, because that was the limit of the dynamometer.

Note the comparison of at least 60% gain in stress, against the 25% gain (Fig. 1) at 1,000,000 cycles, and against the estimate of 10% which was expressed as very conservative in a more general sense. This difference was attributed to the use of a very high degree of coverage which will be discussed later.

In order to illustrate the possible influence of some of the factors on the amount of gain afforded by peening, results of laboratory tests are included in this discussion. For example, Fig. 2 shows the results of tests made by American Standard, Industrial Division (1)*. The specimens were 0.335 in thick and were machined with a fillet of approximately 0.200 in radius on each side. The physical properties of the specimens are shown in Table 2, as are the conditions of peening.

As indicated in Fig. 2, identical specimens were run under three conditions: as-machined, polished, and shot peened. All peening was done on as-machined specimens, that is, without any polishing.

The endurance limit stresses, on the basis of 10^7 cycles, as taken from Fig. 2, are shown in Table 3.

The indication that shot peening is more effective than polishing is quite logical, because in polishing the gain is limited by the extent to which the stress concentration due to roughness has been reduced. On the other hand, shot peening

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*Numbers in parentheses designate References at end of paper.

Table 2 - Peening Tests

Material	SAE 4340 steel
Hardness, Rc	23
Yield strength, psi	81,000
Ultimate strength, psi	109,500, based upon original area, or 150,000, based upon area at rupture
Type of test	Cantilever, reverse bending
Conditions	
Shot	Standard cast-steel 230 (SAE J444)
Shot control, %	85, retained on 0.023 in sieve
Arc height, A	0.013
Coverage	98%

Table 3 - Endurance Limit Stress (Reverse Bending)

	psi	% of Yield Strength
As-machined	25,000	31
As-machined, then polished	41,000	51
As-machined, then peened	52,000	64

introduces a compressive stress in the surface, and reduces the resultant stress thereby. This reduction results in a gain beyond any effect that could be attributed to a reduction of stress concentration due to roughness. The limit of reduction of stress concentration is 1.0, or zero amplification of the actual stress causing failure, whereas if the resultant stress can be reduced by a finite addition of an opposing stress, that limitation disappears.

Even more significant is the fact that the endurance limit stress was more than doubled in comparison to as-machined specimens, and that endurance limit stress is 64% of the yield strength under a stress cycle of complete reversal of stress. Further discussion of these results will be found in Appendix B.

SHOT PEENING CARBURIZED STEEL

The statement has often been made that shot peening is not likely to be effective on carburized gears, because there is a compressive stress at the surface after carburization. It is true that such a compressive stress occurs. But the order of magnitude of the surface compressive stress due to carburization is much lower than that from shot peening.

Evidence of substantial gain in fatigue strength of carburized steel can be seen from the results of a series of fatigue tests on laboratory specimens, made by Wheelabrator Corp.

These tests were made on flat specimens with a thickness of 0.229 in in the most highly stressed area, namely, at the bottom of a transverse notch (5/16 in radius), intended to simulate a gear tooth fillet, cut with a sharp cornered hob and consequently displaying severe machine marks.

Table 4 - Peening Tests

Material	SAE 4620
Heat treatment	Liquid carburized 1/32 in case, quench in oil at 1500°F, draw at 350°F, 58-60 Rc
Type of test	Simple bending (0-max) cantilever
Conditions	
Shot	Cast-steel with high hardness (avg 56.8 Rc) 230 (SAE J444)
Shot control, %	85, retained on 0.023 in sieve
Arc height, C	0.007
Coverage	3.0

Table 5 - Life-Cycles to Failure (Simple Bending) at Maximum Applied Stress of 129,000 psi

Nonpeened, Failed	Peened, Not Failed
27,000	18×10^6
38,000	12×10^6
66,000	10×10^6
68,000	10×10^6
77,000	10×10^6
89,000	10×10^6
	10×10^6
	10×10^6
	10×10^6
	10×10^6

The physical properties of the specimens and the peening conditions are shown in Table 4, and the results are shown in Table 5. After the tests, the peened specimens were rerun at higher stresses, as shown in Table 6.

Note that all of the specimens retested at 155,000 psi were unfailed at 10^7 cycles, and five were unfailed at a stress of 161,000 psi. This indicates an endurance limit of at least 155,000 psi, which is 20% higher than the stress at which all of the nonpeened specimens failed in less than 100,000 cycles. It is interesting also to note that the endurance limit of 155,000 psi was obtained in an area that showed visible machine marks without the aid of any magnification.

PITTING RESISTANCE

In at least some instances of inadequate surface durability, such as pitting of gear teeth, failure is likely to occur as the result of subsurface shear stress due to the contact pressure between the mating teeth. In such cases, peening may be used

Table 6 - Life-Cycles to Failure at Maximum Applied Stress

155,000 psi	161,000 psi	168,000 psi
–	10×10^6 not failed	43,000 failed
7×10^6 not failed	10×10^6 not failed	48,000 failed
–	92,000 failed	
7×10^6 not failed	181,000 failed	
–	75,000 failed	
10×10^6 not failed	10×10^6 not failed	58,000 failed
10×10^6 not failed	97,000 failed	
10×10^6 not failed	10×10^6 not failed	42,000 failed
–	–	80,000 failed
8×10^6 not failed	10×10^6 not failed	102,000 failed

to increase the resistance to pitting. In this type of application, a different approach should be used in the selection of peening conditions.

Since failure is assumed to be due to subsurface shear stress resulting from the contact pressure between the teeth, the arc height is chosen to ensure a substantial compressive stress in the region where this shear stress is maximum in service. With the possible exception of coarse-pitch gears, this suggests a higher arc height than that for bending strength (2).

Due to the possibility of different causes of this type of failure, it is advisable, as in some other applications, to run tests on experimental gears to appraise the advantages.

SCORING RESISTANCE

Although no test results are available to support the concept of increased scoring resistance, it is logical to expect that the increase in bending fatigue strength afforded by peening would allow the use of a finer pitch and consequently shorter tooth height, which would tend to reduce the amount of sliding contact of the teeth.

GEAR NOISE

As in the case of scoring resistance, no direct benefit would be expected in alleviating gear noise by shot peening. But the increase in bending fatigue strength could be utilized to provide a choice of tooth design more favorable to reducing noise.

An example of this procedure is one in which an automotive manufacturer was enabled to change from 10 pitch to 14 pitch in production. The manufacturer reported an attractive reduction in noise level and stated that this change could not have been made without shot peening, because beam failures would have been inevitable in the production gears.

As in the case of scoring resistance, the use of peening for this purpose involves a change to a finer pitch.

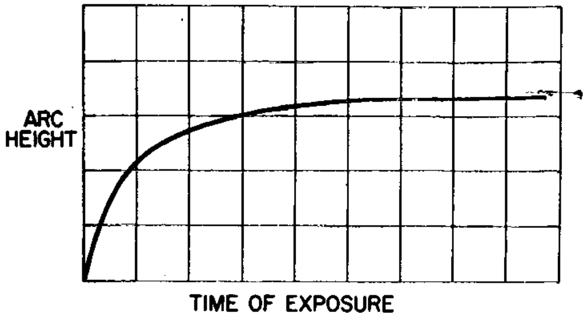

Fig. 3 - Arc height versus time curve (qualitative)

APPLICABILITY OF MATERIALS

As implied in the examples given earlier, shot peening is applicable to all metals that are normally used for high load-carrying capacity.

MEASUREMENTS IN SHOT PEENING

ARC HEIGHT - The most common measurement used in a production peening operation is arc height. This, in brief, is simply what the name implies—measurement of the height of arc or degree of curvature resulting from peening one side of a standard strip of spring steel known as an Almen specimen. It derives its name from John O. Almen, who originated it and the means of measurement. The specimen is mounted on a standard Almen block and is exposed to the blast of shot in as nearly as possible the same manner as the critical area of the workpiece. It is then removed, and its arc height is measured on a standard Almen gage.

The Almen equipment just mentioned is completely described in the SAE Handbook specification SAE J442 (3) and is available from any of the recognized manufacturers of shot-peening equipment.

The measurement of arc height is for the primary purpose of exercising control in a peening operation. It was originally intended for that purpose by appraising the severity of impact of the shot. On a qualitative basis, this is associated with the residual stress imposed by the blast of shot. That is, the greater the impact, the greater the arc height, and the greater the depth of compressive residual stress. With a given blast of shot, the arc height increases with the time of exposure to that blast—rapidly at first, then gradually—until the curve levels off as illustrated in Fig. 3. Qualitatively, the shape of this curve is characteristic of the influence of exposure time, but it is impossible to predict its shape on a quantitative basis, because it is influenced by a number of factors. These include the gradation of the size of the shot in the blast, the method of exposure of the specimen in an attempt to duplicate that of the workpiece (for example, in the simulation of a rotating workpiece of 1/2 in diameter, a drastic variation in the angle of impact on the specimen is inherent during each revolution), etc. This qualitative nature of the curve becomes apparent when we consider the fact that the maximum, or completely leveled-off, arc height can only be that resulting from maximum impact on the specimen from any standpoint; that is, the impact produced by the largest, hardest shot, striking the work at the highest velocity and the maximum angle of impact. The shape of the curve, as it approaches that maximum valve, depends upon how much of the shot striking the specimen is striking with the greatest impact. Actual tests, with identical blast characteristics, show gross differences by changing only the mode of exposure of the specimen. The greater the spectrum of variables influencing the impact, the more gradual the curve in leveling off.

During the early history of shot peening, a convenient description of the curve involved the location of the "knee" of the curve. That is where it begins to show a marked decrease in slope. However, in some cases, particularly when the mode of exposure involves a broad spectrum of impact angles such as in rotation of the work, the knee looses its identity as an abrupt change in shape, and becomes a long, sweeping curve.

COVERAGE - The degree of coverage can be measured on a quantitative basis insofar as the entire blast is concerned. In this case, coverage is defined as that percentage of a given small area of the specimen which has been indented by the blast. The shape of the curve of coverage versus time of exposure is fixed mathematically. It is the same for any blast, and is not influenced by shot size distribution, variations in angle of impact during exposure, etc. The curve can be expressed by (3, 4):

$$C = 1 - (1 - C_1)^n \qquad (1)$$

where:

C = % coverage (expressed decimally) after n cycles through blast
C_1 = % coverage after one cycle
n = number of cycles

The curve is shown in Fig. 4. It will be seen from the curve and from the equation that coverage approaches 100% as a limit as the exposure time is increased indefinitely. Therefore, it is indeterminate at what point on the time scale 100% is reached. It is for this reason that 98% was chosen arbitrarily to represent one unit of coverage. Beyond that point, coverage is expressed as a multiple of the exposure required to obtain 98%. Thus, a coverage of 2.0 designates an exposure time of double that required for 98%.

Fig. 5 has been prepared for quick determination of exposure time required to obtain the reference, 98%, or unity coverage when a measurement has been obtained at a lower coverage. This chart can be used, with accuracy comparable to that of Eq. 1, as follows:

1. Select, on the vertical scale, the percent coverage in one pass indicated in the initial determination. For example, suppose this is 48% coverage in one pass.
2. Simply follow the 48% line to the inclined chart line and read directly on the horizontal scale the number of passes required for 98% coverage. In our example, this is 6.0, indicating that the exposure required to obtain 98% is 6.0 times that required for 48%.

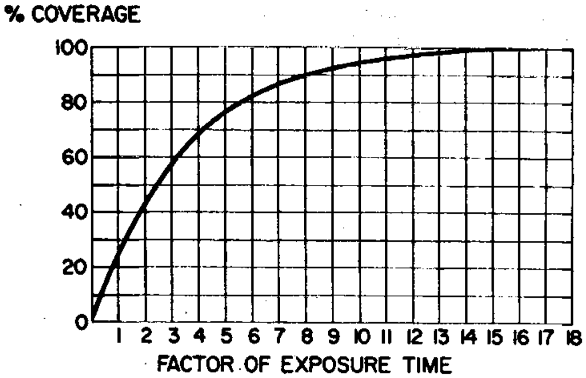

Fig. 4 - Coverage versus time curve (quantitative)

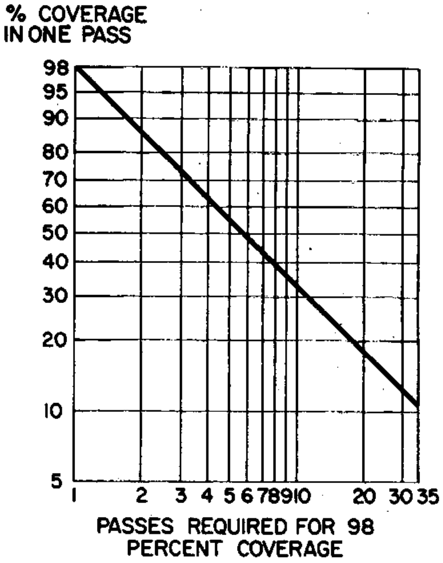

Fig. 5 - Coverage chart for direct computation

For a more convenient form of Eq. 1, let $1 - C = B$ and $1 - C_1 = B_1$. Then, $B = B_1^n$ (B and B_1 = areas not covered). For example, if C_1 = 48%, to determine time for 98%, $B_1 = 0.52$ and $B = 0.02$; therefore, $0.52 = 0.02^n$, from which $n = 6.0$.

This method of interpreting coverage has been a valuable aid in the analysis of the interrelationship of arc height and coverage as influenced by machine conditions.

It can be a useful tool in setting up the conditions of a peening operation and in facilitating the duplication of results in production. However, the measurement of coverage as such cannot be used as an inspection tool or as a means of control in a production operation.

It is equally important to note that, as stated above, coverage as measured by this method includes that produced by any part of the blast, and gives no clue to the amount of coverage that is effective in increasing fatigue strength. As will be discussed in Appendix C, it has been shown that, for example, appreciably undersized shot is ineffective in relation to the full-sized shot in the blast. On a more general basis, a rule was suggested by this author some years ago that the effective part of a peening blast is represented by the largest, hardest shot, striking the work at the highest velocity and at the maximum angle of impact. Here, again, this statement must be recognized as a qualitative one, in that the limits within which a variable is effective have not been completely defined in all cases.

It would appear that, since the arc height-time curve is asymptotic to the maximum obtainable by that particular blast, the curve would be admirably suited to serve as a means of recognizing the utilization of the effective portion of the blast. To a point this is true. In an individual peening job, in which it is vital to obtain the greatest gain with known techniques, this property can be very useful. But a problem arises when we consider the fact that the curve has a variable shape and is also asymptotic to the value in which we are interested. The result is that, although the curve is very useful, it can be difficult to utilize it as a quantitative measure. For example, when the curve is very gradual in the leveling-off region, it can be extremely time-consuming to determine the maximum arc height.

The above discussion is intended to illustrate the necessity of recognizing the qualitative nature of the tools available to appraise truly the degree of effectiveness of a peening job. This does not imply that the tools are inadequate to obtain a very substantial gain in fatigue strength. The fact remains that, even with these qualitative tools, many fatigue problems have been solved which otherwise would have been extremely difficult if not impossible. But, if we are to accomplish the maximum utilization of peening, it is important to recognize the interdependence of arc height and coverage. The relationship of either or both of these variables to fatigue strength has been the subject of investigation for a number of years, and some ground rules have been established on the basis of experience. Since the goal, for the most part, is increased fatigue strength, which in itself has complex relationships, it is entirely understandable that different rules of specifications for arc height and coverage are in use in different shops.

ARC HEIGHT–FATIGUE STRENGTH

Tests on fatigue specimens, and accumulations of data on tests in the laboratory and in the field, have led to a rule used for a number of years. This is a tabulation based on the thickness of the cross section to be peened. It seems evident that the preferred arc height would be a function of this thickness, based upon the fundamental principle discussed in Appendix B, that there must be a balance of forces and moments resulting from residual stresses existing within a peened part. But here again, it is necessary to consider any such rule as a qualitative one, subject to different conditions and requirements in individual cases. As long as we use it as such, it can serve as a guide. The tabulation is shown in Table 7, expressed as the simple thickness of a rectangular beam.

Table 7 - Rectangular Beam

Thickness, in	Arc Height, A
1/16	0.012 N
1/8	0.008
1/4	0.014
3/8	0.018
1/2	0.021
5/8	0.007 C
3/4	0.008 C
7/8 or more	0.010 C or more

This tabulation was used for all hardness ranges and was considered conservative in the sense that the values were chosen carefully to avoid exceeding the optimum for the particular thickness. More recent data, including the tests mentioned earlier on carburized and hardened specimens, have indicated that a considerably higher arc height could be used in case-hardened steel. It will be noted that in that case, an arc height of 0.007 C was used for a thickness of slightly less than 1/4 in, which is quite high compared to 0.014 A in tabulation. It should be further noted, however, that the specimens in that test were machined with transverse tool marks to simulate a severely machined surface.

Note that the above tabulation is limited to thicknesses less than 1 in. Extensive fatigue tests on steels with a hardness of 45 Rc or less have indicated that, for heavier cross sections, the gain in fatigue strength is limited only by the maximum arc height practically obtainable, assuming, of course, that good practice is used. This should be expected from the fact that, for such a thickness, the residual tensile stress below the surface is distributed over such a large area that the magnitude of the maximum residual tensile stress is of no consequence.

COVERAGE–FATIGUE STRENGTH

As can be seen from the above, tests have indicated that the arc height, in limited thicknesses, should not exceed a limiting value if it is to be most advantageous.

Repeated testing of fatigue specimens has shown a definite tendency for increased gain in life as the coverage is increased, provided that limiting value of arc height is not exceeded. This tendency prevailed even when the coverage was in multiples of 98%, and the time of exposure was well beyond the apparent leveling-off point of arc height. Since this was a surprising tendency, a large number of tests were run at successively higher coverage, but with the same arc height. That is, if, at the higher coverage, the arc height was measurably higher than at the previously tested coverage, the velocity was reduced accordingly. In these particular tests, no limiting value of coverage appeared within a multiple coverage of 7.0. The life increased with coverage up to the highest coverage used. But in the same series of tests, at an arc height that appreciably exceeded the limiting value (in a test specifically run to determine this influence), the life was no greater than that obtained at 98% coverage.

Before attempting to utilize this trend, the economics should be carefully considered in relation to the degree of gain, which once again must be considered on a qualitative basis, due to the many variables previously mentioned. Whereas the life, under the above conditions, increased rather rapidly with coverage in the earlier stages, above the region of 98%, it was quite gradual; that is, much less than in proportion to the additional time required for multiple coverage. This is not surprising in the light of the fact that coverage approaches 100% as a limit. For example, the time required to increase coverage from 80 to 98% is almost a ratio of 2.5:1. In making this comparison, it must be remembered that the figure of 98% is not an absolute value, but one that was chosen arbitrarily because of the nature of the curve. It must be remembered also that the asymptotic nature of this relationship is an inherent characteristic of coverage, regardless of the method used to measure it.

Beyond the 98% point used in the above comparison, the coverage curve becomes even more gradual or flat, and consequently even more demanding of time. This leads to the conclusion that, to justify the use of multiple coverage, it is necessary to weigh the advantage against the cost. If the cost of peening is a small fraction of the overall cost of manufacturing the component being peened, as in the previous example using a coverage of 7.0. The cost of peening at this high coverage could be advantageous. On the other hand, small automotive gears, for which the production cost has been minimized by high-volume production, may not be a candidate for such a choice. An attempt to explain the above indications is given in Appendix C.

In discussing the influence of coverage, the reference to exposure time has been based on a constant flow rate. Under that condition, an increase in coverage would entail a corresponding increase in cost. However, it may not be necessary to depend entirely upon increased time of exposure. It may be practical to increase the shot flow rate. With a given peening condition, the time of exposure will vary in inverse proportion to the flow rate. In wheel type of equipment, it is a simple matter quantitatively to predetermine what flow rate is most advantageous in relation to exposure time, power requirements, etc.

Although multiple coverage, as discussed above, can be very useful for limited cross sections, in dealing with parts in which the most highly stressed thickness is on the order of 1 in or greater, it is more direct, more effective, and probably more economic to use a higher arc height at a more moderate coverage. This is not necessarily a function of the size or weight of the overall component, but rather the thickness of the most highly stressed area. For example, a gear may have an enormous size but a limited tooth thickness.

Assume we are dealing with a driveshaft having a diameter of 1 in in the area where fatigue failure is most likely. Assume further that it would be attractive to use the same shaft in a larger vehicle, but its fatigue strength is known to be inadequate for that purpose. In such a case, there is an excellent possibility that peening would provide the necessary increase. Two of the many choices of peening conditions could be:

1. 390 cast-steel shot, 0.009 C arc height, and a coverage of 3.0.
2. 550 cast-steel shot, 0.013 C arc height, and a coverage of 98%.

Comparing these options, it is likely that item 2 would provide at least as much gain as 1, because of the higher arc height and correspondingly deeper compressive stress. Because of the high coverage requirement, the cost of item 1 would be higher in terms of both labor and shot. From every standpoint, then, the higher arc height at moderate coverage would be likely to provide a greater gain at lower cost, when peening this large cross section.

SHOT SIZE

A given arc height and coverage can be obtained with large shot at low velocity, or with smaller shot at correspondingly higher velocity. The latter will meet the specification with less shot, or higher conveyor speed and therefore less cost. This is because the rate of coverage is so strongly influenced by the number of pellets per pound of shot. Since the volume of a pellet varies directly with the cube of its diameter, the number of pellets per pound will be inversely proportional to the cube of the diameter. It is true that the size of the indentation with the large shot is greater, but this is far outweighed by the strong influence of the number of pellets per pound.

It is interesting to note that the use of the concept of 98% coverage permits a quantitative comparison of such costs, by virtue of the fact that coverage can be eliminated as a variable. With its use, experimental results have shown that, when all of the factors are taken into account, the conveyor speed for a constant arc height and coverage varies inversely with about the cube of the shot diameter.

Whatever the selection of shot size, it is important that the size in circulation in the peening machine be uniform. In any production operation, the shot will break down as an inherent result of the impact doing the work. This is a fatigue type of failure, and the split shot subsequently fractures into successively smaller particles until they are removed by the separator. The spent shot, unless removed at the proper size, will result in the dilution of the effective shot in circulation. It has been shown that appreciably undersized shot is ineffective in a peening operation, and therefore "goes for the ride," leaving only the full-sized shot to accomplish the effective peening. The importance of maintaining a high percentage of full-sized shot resides in the fact that, for a given level of peening quality, it will result in better economy under ordinary conditions. The term "peening quality," as used here, is based upon fatigue strength rather than simply upon meeting the specification of arc height and coverage. This is a factor that is often misunderstood in terms of immediate data on shot consumption. If, for any reason, undersized shot is accumulated in the machine, the rate of breakdown and the resultant rate of addition of new shot will decrease. On the surface, this would appear to be good, because of economy. However, at a given conveyor speed, this dilution is likely to result in a lower arc height. Even more important, the amount of effective coverage will be reduced, at the expense of less gain in fatigue strength. Now, to compensate for the reduced arc height, it will soon occur to the operator that the shot velocity could be increased or that the next larger shot size could be used.

Either of these procedures would be capable of adjusting the arc height to meet the specification. But, unfortunately, the result leads to an even higher percentage of ineffective shot, or more dilution of the effective shot. Finally, this leads to lower efficiency in the peening operation, and higher cost, in terms of the true product of the peening machine–increased fatigue strength. The above statement deals with the percentage of full-sized shot in the peening machine, and has nothing to do with the distribution of size in the specification for new shot. The shot size specification SAE J444 is entirely adequate for new shot, and, in the experience of the author, any reduction of the tolerance is likely to increase the cost of shot without providing any benefit to compensate for it. In the final analysis, in an automotive application for shot peening, the primary purpose of the process is an increase in load-carrying capacity at the least cost.

TYPE OF SHOT

There are a number of types of shot available, including cast-steel, cut steel wire, cast-iron, and glass beads. The most likely to be used in automotive applications are cast-steel and cut wire. Due to the availability in all sizes, and its durability, cast-steel is the one in most common use. Generally, this material is available in two hardness ranges. The more common is 40-50 Rc, which is used for the majority of applications in the range of spring hardness or lower, and in some cases for the harder materials. The other is in the range of 51-59 Rc, with an average of 56.5. Since shot breakdown is a fatigue type of failure, it is subject to the tendencies expected in the sense that for hardness in excess of about 40-50 Rc, the notch sensitivity is likely to reduce its durability. Shot breakdown tests have shown that the harder shot is subject to a higher rate of breakdown under similar conditions. In the case of peening components of high hardness, such as carburized and hardened gears, this increased breakdown could be justified in some cases by the fact that better results can be obtained. This is particularly true in cases where the surface being peened has been machined with severe cutter marks, such as gear tooth fillet without the benefit of a rounded hob top. Presumably, this is due to the peaks and valleys left by the cutter. When the work is harder than the shot, permanent deformation of the shot occurs prior to that of the valleys. Consequently, the depth of penetration of the residual compressive stress is reduced. In case of doubt about the most appropriate choice of shot hardness, the most positive solution resides in fatigue tests for the purpose of separating the factors of increased fatigue strength and cost of the peening operation.

Glass beads can be used very effectively in cases involving the use of very thin sections. For example, a very thin leaf spring, say on the order of 0.020 in, lends itself to the use of particularly low arc height, and control of that low arc height is particularly important. Glass beads are available in considerably smaller sizes than any obtainable in the metallic types.

Glass beads are also very useful in cases where minute deposits of metal on the surface must be avoided. Such applications are more common in parts made of nonferrous materials, or where components must be electroplated after peening.

In the case of especially thin cross sections, a low value of impact is desirable for two reasons: to avoid warpage and to obtain a very shallow layer of compressive stress which is likely to be most effective in increasing fatigue strength.

SHOT VELOCITY

Earlier, there was the implication that for a given arc height and coverage, it is most economic to use the highest velocity practicable, and corresponding shot size. This is true in spite of the fact that the rate of breakdown of shot is very strongly influenced by the velocity. The compensating factor is that when the shot size and velocity are chosen to give the same arc height and coverage, the conveyor speed is similarly influenced. The result is that the shot consumption per piece peened is very nearly the same, and the higher conveyor speed remains a clear advantage.

INSPECTION

Generally speaking, visual inspection of the surface of parts after peening will reveal obvious lack of coverage due to malfunction of work handling equipment, obstruction of the flow of shot, etc.

A visible change in surface appearance may indicate a severe increase in accumulated undersized shot, but this is likely to be preceded by a decrease in arc height.

It is impractical to describe a peened surface in the general sense, other than to say that materials of low hardness, peened with high arc height, will show a very rough surface. A fully hardened surface, on the other hand, is likely to be roughened so slightly as to appear nonpeened, particularly for low arc heights or when steel shot of the standard or lower hardness is used. Strictly speaking, coverage, either visual or measured, is not a good means of production control.

Measurement of residual stress distribution in the cross section of the part is impractical as a production inspection tool, because of the time-consuming removal of layers and repetitive measurements. If failure, even after peening, is most likely to occur at the surface, it is advantageous to determine the magnitude of residual stress there. X-ray diffraction offers a means of this determination as a spot check, involving some delay in its measurement and possibly transportation of the samples to the laboratory.

A relatively new process has been developed that appears to be more practical for this purpose. It is called "Fastress" (4) and is capable of measuring the surface stress by means of x-ray diffraction in but a fraction of the time ordinarily required. This is a nondestructive test, so that, in some cases, it could be practical as a production control tool, provided surface stress is the controlling factor.

FACTORS INVOLVED IN SELECTION OF PEENING CONDITIONS

It is good practice, whenever possible, to run fatigue tests to appraise the real benefit that might accrue in a given application. It is quite likely that such tests will pay for themselves in the form of lowered cost of the production peening process, even in some cases where peening is already employed. In many cases, however, tests are impractical, and it becomes necessary to appraise the benefits on the basis of available information and trends that might be expected.

MAXIMUM APPLIED TENSILE STRESS

As illustrated in the fatigue charts in Figs. 1 and 2, assuming a constant peening condition, a greater increase in durability is likely to be obtained at lower levels of applied tensile stress, or correspondingly longer life. Accordingly, it would be expected that even a moderately good peening job would accomplish a good gain at low applied stress. Conversely, at higher stresses, the peening conditions would be expected to be more demanding for the same order of gain. Due to the difficulty of determining realistic values of actual applied stress in some cases, there is a tendency to associate long life on the nonpeened part with low applied stress. In comparing applications involving similar stress ranges, this is a convenient procedure. However, in using this comparison, it is important to consider the possible influence of applied stress range, which is discussed below.

STRESS RANGE

After considering a number of comparisons of gain under different conditions, the author noticed a trend based upon the above observations. It appeared that greater gain is associated with a lower magnitude of maximum applied tensile stress, even when the maximum is influenced by stress range.

For convenience in this discussion, let stress range during a cycle be represented by the expression

$$\text{stress range (SR)} = 1 - \frac{\text{min stress}}{\text{max stress}} \qquad (2)$$

in which tensile stress is positive and compressive stress is negative. For example,

$$\text{for reverse bending, (SR)} = 1 - \frac{-\text{max}}{+\text{max}} = 2.0 \qquad (3)$$

$$\text{for simple bending, (SR)} = 1 - \frac{0}{\text{max}} = 1.0 \qquad (4)$$

for one-direction bending with a preload of 1/2 max,

$$\text{(SR)} = 1 - \frac{1/2\ \text{max}}{\text{max}} = 0.5 \qquad (5)$$

In reverse bending, the theory of Goodman and Gerber indicates that the endurance limit stress (max) is likely to be considerably lower for given physical properties of the steel than would be the case for simple bending. If the noted trend is representative, then by virtue of the lower maximum tensile stress permissible in reverse bending for a given life, we would expect more gain from peening in the case of reverse bending than for a lower stress range (simple bending). This trend is supported by the example in Fig. 2, in which the endurance limit stress in reverse bending was increased over 100%, despite the appreciable reduction in the residual compressive stress at the surface by virtue of the applied compressive stress in the first cycle. (Examples of reverse bending in service would include idler gears, axle shafts, etc.)

With a lower stress range, the permissible maximum applied stress for a given life is higher; therefore, on the same basis, the gain in fatigue strength by peening would be less. Note the marine gears and the carburized specimens in earlier examples, in which the stress range was 1.0. Even though there was no part of the cycle in which the maximum resultant compressive stress was likely to exceed the yield strength, the gain was not as great as 100% in stress. (Examples of this stress range would include single-mesh, one-direction gears.)

A still lower stress range would be represented by chassis springs (leaf, coil, or torsion bars) in which a preload is involved, representing the weight of the vehicle in the stationary position. In this case, we would expect a higher maximum applied stress for a given life, and therefore less gain by peening.

In the case of a very low stress range, the permissible stress is quite high for a given life, so that on the same basis it would suggest that even for a long life in the nonpeened condition, the gain in fatigue strength by peening would be less than for the higher stress ranges. One instance here is a fatigue test on automotive wheel rims. With a nonpeened life of a million cycles, based on simple bending, we would expect a life increase of 5-10:1, if the rims were peened. Thus, the nonpeened life would suggest an "easy" gain. But when the rims were peened, the gain was only on the order of 2-3:1.

FATIGUE TESTS FOR APPRAISAL OF PEENING

The foregoing discussion illustrates the importance of duplicating, as nearly as possible, the conditions to be encountered in service when running a fatigue test to appraise the possibilities of peening in a particular application. It is understandable that, for example, rotating beam specimens (stress range of 2.0) would be used to determine the fatigue strength of various materials. It is a simple, relatively easy procedure to measure the load precisely and to maintain it throughout the duration of the test. But when such a test is used to simulate a component in service, it is necessary to recognize differences that may exist between the laboratory test and the conditions that obtain in the service of the component. Such a test would not be representative for peening a part for simple bending. In addition to the precaution against being misled by such factors as stress range, it is important to recognize the vast difference in peening requirement that might be indicated if the cross-sectional thickness of the laboratory specimens is appreciably different from that of the components they are intended to represent. This has been the source of confusion in more than a few cases. For example, a fatigue test is very carefully conducted on R. R. Moore fatigue specimens, very carefully made and treated to duplicate precisely the material used in a rather complex part with a thickness in the most highly stressed section of 1 in, and subjected to a stress cycle that is difficult to determine, but is in no way comparable to reverse bending. Excellent results are obtained in the laboratory tests, but when the component is shot peened under identical conditions, the results are quite dissappointing. Obviously, the reverse could be true, in that the laboratory test could have been such as to discourage further consideration of peening in an application where peening could be of value.

CONTROL OF SHOT PEENING

When we consider that the product of a peening operation is fatigue strength, which is not only an invisible property but a very elusive one, it is not surprising that any inspection of that product is not simple.

Control of the peening operation involves control of the process itself and requires surveillance of:

1. Arc height–periodic measurement.
2. Shot in circulation–periodic sieve analysis.
3. Separator–maintenance of uniform curtain of shot cut by the airstream, proper airflow, constant discharge of spent shot.
4. Adding device–positive assurance that the hopper of this device is adequately supplied with new shot.

The emphasis on new shot results from experience on more than one occasion in which the adding device was kept full of spent shot which had been removed by the separator. It would seem obvious this defeats the purpose not only of the adding device but also of the separator.

5. Shot velocity–in wheel type of equipment, this is simply a matter of maintaining a constant wheel speed.
6. Shot flow rate–foreign matter such as paper, rags, etc., in the hopper or circulation system can obstruct the flow of shot. In wheel type of equipment, this will be reflected in the reading of the ammeter that is usually installed on production machines.
7. Conveyor maintenance–repair or replacement of worn parts that might affect the conveyor speed, indexing rotation, or other properties of exposure of the workpiece to the blast.
8. Shot stream–inspection of wheel parts, including blades, impeller, control cage for wear and proper adjustment of control cage, or of nozzles, orifices, air lines, filters, pressure regulators, etc., in air type of equipment.

Probably the most common problem of control in a production peening operation is that dealing with the shot in the machine. This is due, at least in part, to the interrelated influence of shot size, shot consumption, arc height, and fatigue strength. When these are put in their proper perspective, there is little or no problem in maintaining efficient control. This is a matter of maintaining a high content of effective shot striking the work. With a good separator and a level control type of adding device for makeup, the adjustment of the separator will establish the particle size removed, and, in turn, the amount of full-sized shot in the machine. That is to say, with a given adjustment, after the machine has run continuously for a sufficient period, the particle size distribution of the shot in the machine will become constant. If, with that adjustment, the accumulated undersized shot is excessive, the airflow through the shot curtain of the separator should be increased. This increases the particle size removed, thereby reducing the amount of undersized shot in the machine when the particle size distribution again becomes constant. By successive adjustments, the desired content of full-sized shot is obtained in a stabilized condition. No further adjustments are necessary. Good surveillance of the separator and the maintenance of an adequate supply of new shot in the adding device will retain that stabilized condition. For efficient operation, under ordinary conditions, it is recommended that 85% of the shot in the machine be full sized. That is, for example, if 330 shot is being used, 85% of the shot in the machine would be retained on a sieve with an opening of 0.033 in. In a production machine, oversized shot is not likely to be excessive, unless it is an unusually high percentage (beyond the specification) in the new shot added.

EQUIPMENT FOR PEENING

The most obvious requirement in a machine for shot peening is the means for accelerating the shot to the desired velocity. This device may be in the form of a centrifugal wheel or an air nozzle. There are two types of nozzles: the induction type and the direct-pressure type.

In the centrifugal wheel type, the shot is accelerated by the blades of a rotating wheel after entering at its center through an impeller and a control cage. Fig. 6 shows a phantom view of a Wheelabrator unit and illustrates the fan-shaped blast pattern as the wheel rotates, in this case, in a clockwise direction.

For high-volume production, the wheel type is the most economic because of its capability of delivering shot at very high flow rates with a fraction of the power required for the compressed air types. For example, one Wheelabrator unit will throw more than 300 lb/min with an expenditure of 15 hp. With the direct-pressure type, this would require five nozzles 3/8 in diameter at an air pressure of 80 psi and would require 190 hp (this is for comparison). The same wheel is capable of throwing over 1000 lb/min, at which 40 hp would be required. Larger units, of course, have even greater capacity, but the choice of size will depend upon the production and volume requirements.

One advantage of the wheel type is the fact that acceleration of the shot is provided by physical contact with the blades, and therefore the shot velocity is a fixed value with a given wheel speed, assuming, of course, that the unit is reasonably maintained.

This consistency of shot velocity is evidenced by the fact that it is rarely necessary to run a test for an arc height-time

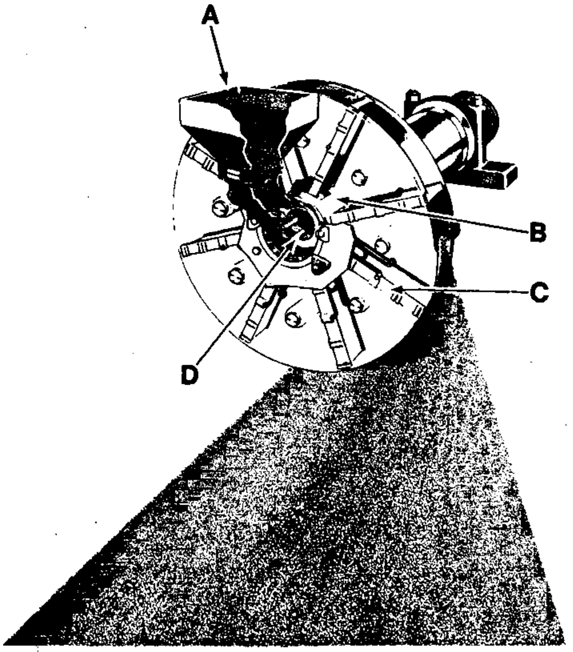

Fig. 6 - Phantom view of wheelabrator. A - shot feed funnel, B - stationary control cage, C - blades, D - impeller

curve on a production machine. Wheel speed, shot size, conveyor speed, etc., usually can be predetermined to obtain a given arc height and coverage.

The wheel unit itself is a self-contained device and requires no compressed air for its operation.

In the induction type of nozzle, the shot enters the air expansion chamber of the nozzle at a point just beyond that of the airflow from the jet. It can be fed by gravity from an overhead hopper, which provides a means of metering the shot flow, or it can be entrained to the nozzle by the partial vacuum within the nozzle. The shot flow rate is quite limited in the induction type, but the air consumption is correspondingly lower in terms of cubic feet per minute, due to the fact that the air jet is about half the diameter of the nozzle.

In the direct-pressure type, the shot enters the airstream under pressure in a mixing chamber directly attached to a pressure tank, then travels with the air through a hose, and finally through the nozzle. The velocity of shot is usually somewhat higher, and the shot flow rate can be higher, for a given air pressure, than in the induction type.

Where the inside of deep holes or cavities is to be peened, it may be necessary to use the compressed air type (preferably direct pressure) with a long nozzle.

In cases requiring a small portion of the surface of an intricate part to be peened, it will often be more economic and more convenient to use the compressed air type rather than the broad coverage of the wheel type.

For laboratory work, or very low production, the compressed air type can sometimes be economic because of the low investment, provided the available supply of compressed air is adequate and no investment in a compressor is necessary.

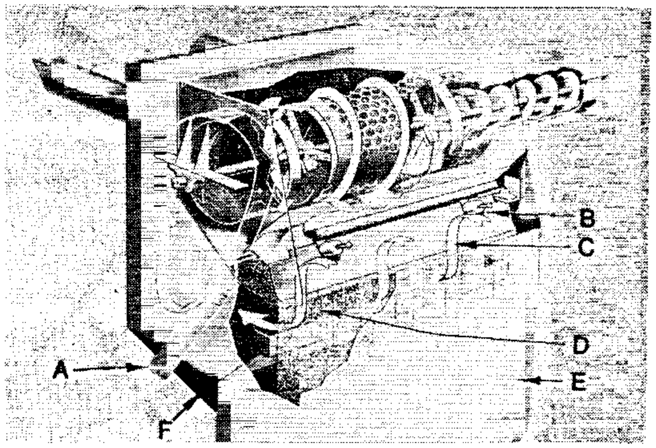

Fig. 7 - Phantom view of separator. A - stray refuse pipe, B - weighted baffle, C - airflow, D - shot curtain, E - storage hopper, F - to spent shot hopper

For any peening application, the type of equipment should be chosen after full consideration of the size, configuration, variety, and quantity of the parts to be peened.

SEPARATOR

As implied earlier, a good separator is a vital part of a machine for production peening. Fig. 7 is a phantom view of an airflow separator. The airflow is supplied by the dust collector and exhaust system which is used for the primary purpose of maintaining cleanliness inside the peening cabinet.

An adding device is also a vital part of the machine, and is for the self-evident purpose of automatically replacing the spent shot. Fig. 8 shows an adding device based upon the principle of a level control. When the shot level drops due to removal of spent shot, the level probe actuates the electrical control unit, which opens a "dipper" valve, thereby allowing new shot from the adding hopper to be added to the system. When the shot level is restored, the valve is automatically closed. This requires a relatively small addition of new shot. With this type of adding device, the rate of addition of new shot is completely dependent upon the rate at which spent shot is removed by the separator, and therefore requires no adjustment.

The importance of these two items has been implied earlier, but long experience has indicated a tendency to neglect them. For this reason, it might well be repeated that the separator should be adjusted to maintain efficient operation of the entire process, and this cannot be accomplished without the certainty that the adding device is adequately supplied with new shot at all times.

HANDLING EQUIPMENT

It is important to select the type of equipment that will expose the parts to the blast for the best utilization of the shot. This includes both the shot acceleration unit and the handling equipment.

Whenever practical, it is advantageous for the shot to strike

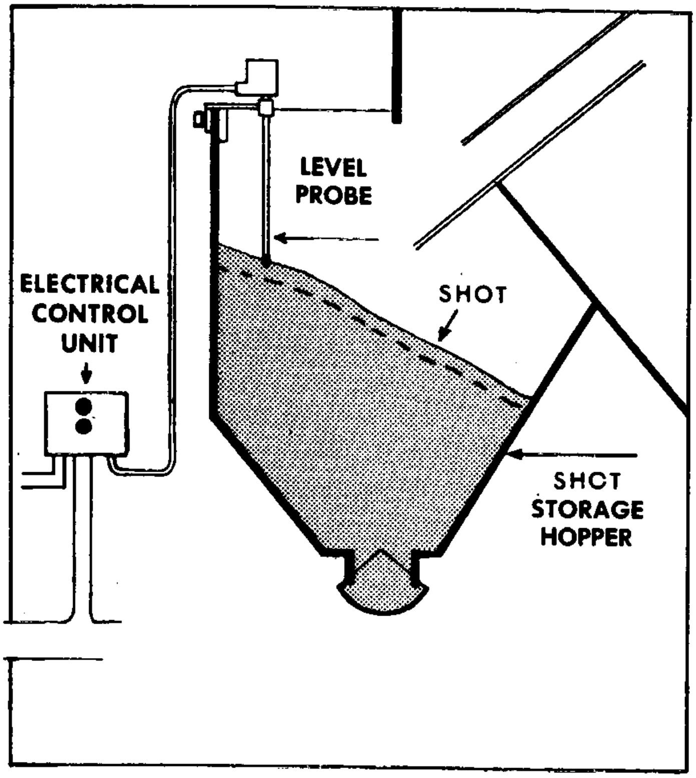

Fig. 8 - Level control type of adding device automatically adds shot to replace that removed by separator

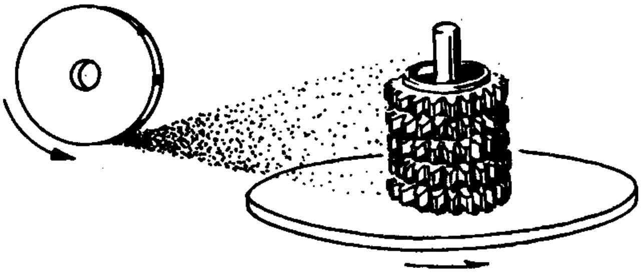

Fig. 9 - Indexed arrangement for peening spur or helical gears

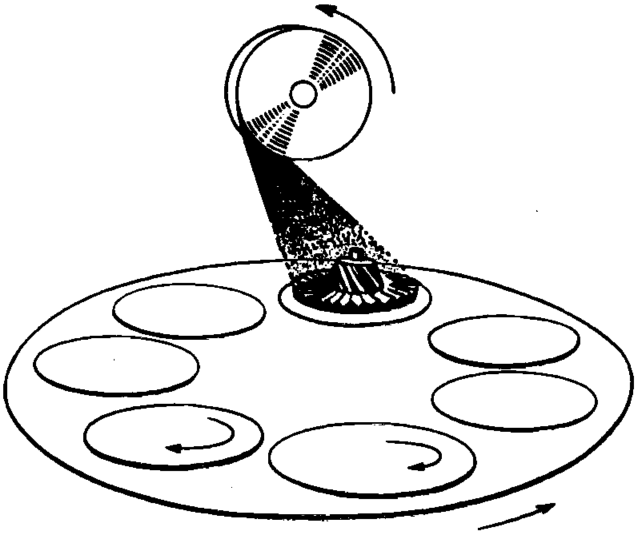

Fig. 10 - Indexed arrangement for peening bevel gears

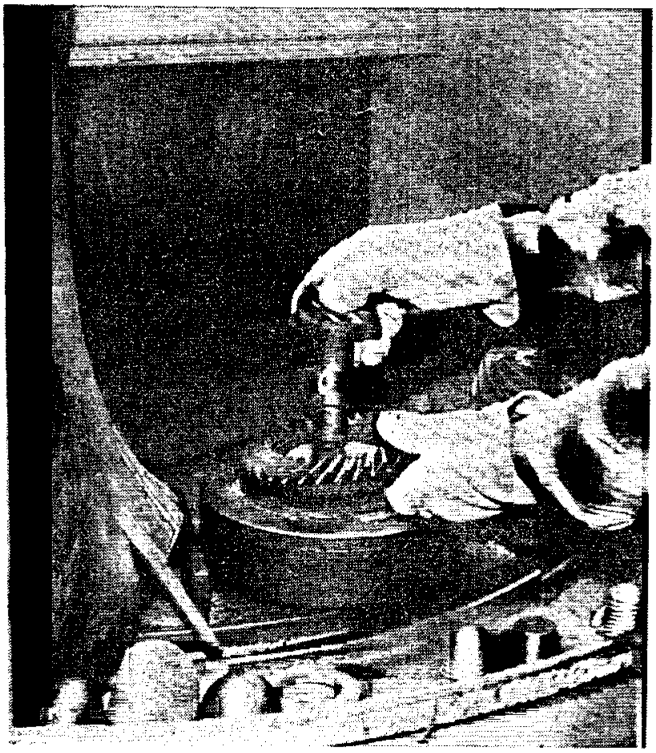

Fig. 11 - Loading matched set of bevel gears on multitable machine

the surface of the critical area at right angles. This is because the required arc height can be obtained at the minimum shot velocity (arc height varies directly as the sine of the angle of impact) (4). However, it is not necessary for good-quality peening. In the case of gear teeth, for example, it may be im-

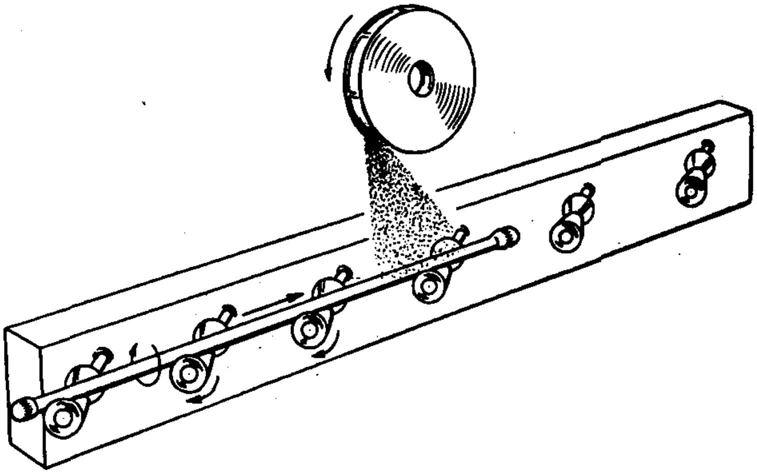

Fig. 12 - Skew rolls for shafts or torsion bars

practical for the shot to strike at right angles to the root fillet, because of the shadowing effect of the adjacent teeth. It is an advantage, however, to have it strike at a uniform angle, in the same sense as that discussed earlier with respect to shot size.

In mounting the Almen specimen for arc height, it is desirable for the surface of the specimen to duplicate that of the workpiece. Logically, the specimen surface would be in the same plane as the critical surface of the work. But in many cases, the true duplication must be recognized as impossible. Such impossibility is immediately apparent in a spur gear tooth fillet, which could be likened to a circular groove, possibly with a 1/8 in radius and 1 in long. The futility of attempting to simulate this with a flat surface, 3/4 in wide, and 3 in long is apparent. But this does not prevent obtaining a very effective peening job on that part. The function of the Almen specimen is to enable the duplication of peening conditions prevailing for the experimental parts leading to the adoption of peening in production. It is a parameter, or yardstick, and was never intended as a quantitative measure of fatigue resistance or of residual stresses in the part. A certain amount of judgment is necessary to obtain meaningful results.

In peening gears in the root fillets, it is usually adequate and practical to mount the Almen block on a rotating fixture so that the longitudinal surface of the specimen is tangent to the root circle and the length of the specimen parallel to the axis of the gear.

In setting the direction of the blast from a wheel, it is necessary to recognize that the direction of the shot is tangent, not to the outside diameter, but rather to a circle approximately 82% of the outside diameter. For example, in a 19-1/2 in diameter wheel, this direction is tangent to a 16 in diameter, or 8 in radius.

In air equipment, the nozzle bore, rather than the nozzle body, should be lined up with the work.

Fig. 9 illustrates an indexed table for peening spur or helical gears. Gears of short length can be stacked one on top of the other to a height of 10-12 in and peened simultaneously. An advantage of this arrangement is that at any given height, the shot strikes at a constant angle. The difference in arc height at various levels is not measurable. This is a highly efficient arrangement and gears can be peened in high-volume production at low cost, even at multiple coverage.

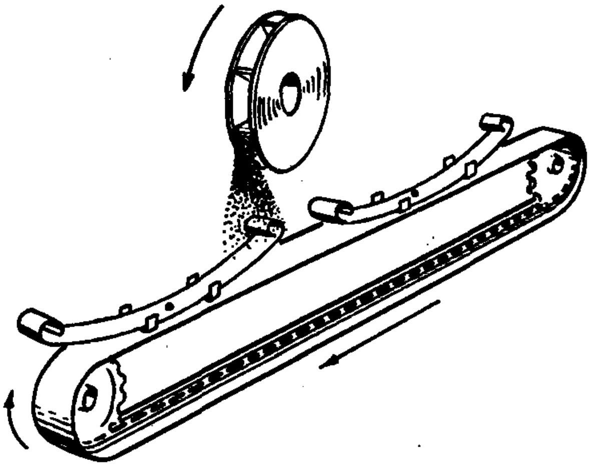

Fig. 13 - Leaf springs, longitudinal travel

Fig. 10 shows a similar arrangement for peening bevel gears. In this case, the wheel is mounted in the roof of the cabinet instead of in the side wall as in Fig. 9. This shows a gear and pinion being peened in a matched set. The blast direction is set so that the angles of impact with the root cones are substantially equal. This maintains the efficiency of rotating in an indexed position, with a minimum loss of arc height.

Fig. 11 shows a Multitable machine of the arrangement of Fig. 10. One operator loads and unloads the gears at the front of the machine where the tables are free to rotate but are not driven. As soon as the individual table enters the blast zone, it is automatically driven at a constant speed of rotation as it approaches the indexing position.

Fig. 12 illustrates a skew roll setup for simple shafts. The shaft, or torsion bar, is rotated and advanced axially in the proper relationship by adjusting the angle and rotational speed of the skew rolls.

Fig. 13 shows an arrangement for peening leaf springs on the

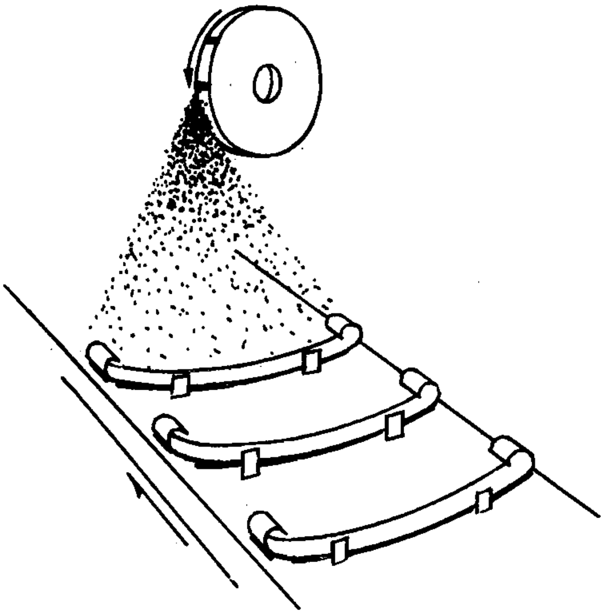

Fig. 14 - Leaf springs, transverse travel

concave side as they travel through the blast in a lengthwise direction.

In cases where it is adaptable, utilization of the blast can be more efficient by transverse travel of leaf springs, as illustrated in Fig. 14.

The above illustrations are for the purpose of showing some typical installations. A wide variety of arrangements is available for peening different configurations under different requirements.

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APPENDIX A
ANALYSIS OF SOME RESULTS

It will be recalled that a gain of over 100% in endurance limit stress was obtained by shot peening fatigue specimens subjected to complete reversal of bending stress.

This means that in the half cycle, which is repeatedly subjected to compressive stress, whatever residual compressive stress prevailed in the as-peened specimen is added to the stress applied during the compressive part of the first cycle.

When we consider that the yield strength of this material is 81,000 psi and the applied stress at the surface is successively 52,000 psi in compression and then in tension, the resultant stress during the compressive part of the cycle will far exceed the yield strength of this material. After the first few cycles, then, the residual compressive stress would be expected to be substantially the difference between the yield strength and the alternating stress. (81,000 minus 52,000, or 31,000 psi).

If no failure occurs at an applied stress of 52,000 psi, and the residual compressive stress at the surface is 31,000 psi, then the resultant tensile stress at the surface will be 52,000 minus 31,000, or 21,000, which is below the endurance limit for the nonpeened specimens. Assuming the stress concentration due to surface roughness is not significantly changed by peening, this appears to be quite reasonable correlation of fatigue properties with the residual stress at the surface.

But the point of real significance is the fact that, in spite of the relaxation of some of the residual compressive stress at the surface, the endurance limit in reverse bending, after peening, is 64% of the yield strength.

However, in material with a hardness of 23 Rc and a corresponding yield strength of 81,000 psi, the residual stress at the surface immediately after peening would be expected to approach the yield strength, or 81,000—far greater than the 31,000 psi just estimated.

Suppose that this group of specimens had been subjected to a fatigue test involving simple bending; that is, a stress cycle of zero to maximum tension stress. At no time during any stress cycle is the peened surface subjected to an externally applied compressive stress. Therefore, there is no reason to believe that the loss of residual compressive stress would even approach that of the above example, if, in fact, there is any reduction of residual compressive stress in the surface at all. This subject has been discussed at considerable length in the literature, but this author has not seen any evidence that, to his satisfaction, gives support to the assumption that there is a loss of residual compressive stress in the peened surface due to a stress cycle that does not include applied compressive stress. In fact, based upon elementary mechanics, yield (which, in a stress cycle at room temperature, is the only source of a change in residual stress) can take place only when a stress or strain occurs that approaches the yield strength of the material.

The above example in reverse bending has been cited primarily to illustrate that even with a relatively low magnitude of compressive stress at the surface, substantial gain in fatigue strength can be obtained. The term "relatively low," however, should be clearly associated with the much greater magnitude of compressive stress resulting directly from the impact of the shot.

Another purpose of including this example is to illustrate that the magnitude of the residual compressive stress at the surface is not the sole criterion of gain. This is implied by the fact that in simple bending, the critical surface is not subjected to a compressive applied stress. Therefore, the magnitude of residual compressive stress at the surface would be appreciably higher after the first few cycles than in the case of reverse bending. If, in fact, this magnitude is an indicator of gain, then a part in simple bending would be in line for a gain of more than the 100% in endurance limit stress. This author's experience has not included such an occurrence.

This cannot be interpreted to mean that the surface compressive stress is not important. Rather, it means that a more realistic property is the distribution of residual stresses, including the surface and any subsurface region at which a high resultant tensile stress might occur.

APPENDIX B
RESIDUAL STRESS DISTRIBUTION

In general, the residual compressive stress produced by the impact of shot is usually of a relatively high magnitude at or near the surface that has been peened. It may be maximum at the surface, or at some small distance below the surface. In any case, the magnitude of the compressive stress at the surface is likely to be rather high. That is, for steel, it is likely to exceed 70,000 psi if the coverage is 98% or greater.

The residual compressive stress decreases rather rapidly from the maximum and reaches zero at a depth depending upon the hardness of the material peened and the conditions of peening. For a given hardness, the depth to zero stress increases with arc height, as a general rule.

An example of a residual stress distribution curve is shown in Fig. B-1. This curve was derived on the basis of measurement of the residual stresses at and immediately below the peened surface, which is shown at the bottom of Fig. B-1. The measurements were made on a flat steel bar, 1/4 in thick, 40 Rc, and 2 in square. Fig. B-1 shows the thickness of the bar in the vertical dimension. Such measurements are made by successively determining the stress at and below the surface, removing thin layers of material, determining the stress at each depth, and repeating the process until the residual stresses due to peening are removed, after which no further measurements can be made. In Fig. B-1, the shape of the curve beyond the actual measurements has been constructed on the basis of equilibrium of forces and moments. That is, considering one unit of width of a 1/4 in beam, the area under the curve bounded by the stress line represents a force in the direction of the stress. Thus, the area of the compressive stress curve at the bottom of Fig. B-1 is equal to a force to the left. The area in tension in the middle portion of the thickness is a force to the right, and the triangle at the top is a force to the left. The sum of the tensile forces (to the right) must be equal to the sum of the compressive forces (to the left). In similar fashion, summation of the moments of these forces about any point must be zero, because the beam with no external forces is in equilibrium. The construction of the estimated portion of the curve is based upon a further assumption. Inasmuch as the material below that which was subjected to plastic flow is stressed elastically, the stress in that portion of the curve is taken as a straight line. With these rules, the curve was balanced by trial and error, estimating the shape between the straight line and the actual measurements.

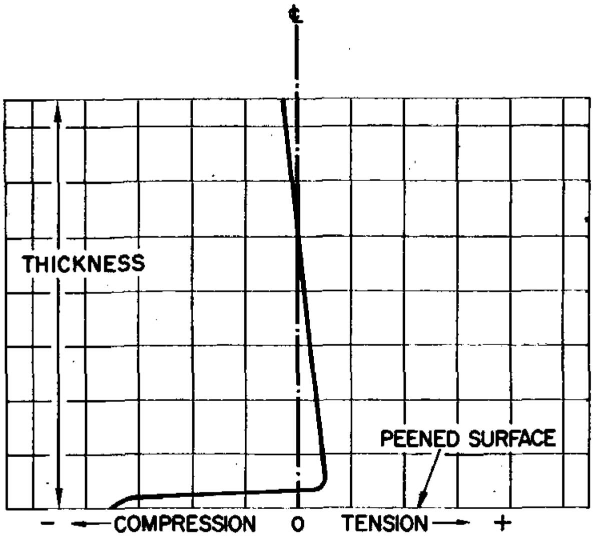

Fig. B-1 - Residual stress–peened on one side

It should be mentioned that the curve in Fig. B-1 is based upon steel of a relatively low hardness (40 Rc). In material of higher hardness, the curve may have an inflection point; that is, the maximum compressive stress may be located a short distance from the surface. In any case, the magnitude of the compressive stress at the surface is likely to be rather high. If an external bending moment is applied to a simple rectangular beam, the distribution of applied stress can be shown as in Fig. B-2.

If we now apply an external bending moment to the beam in

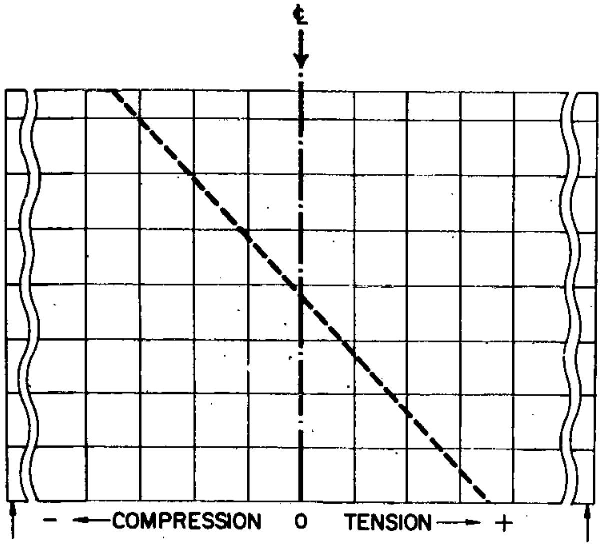

Fig. B-2 - Bending stress due to applied load

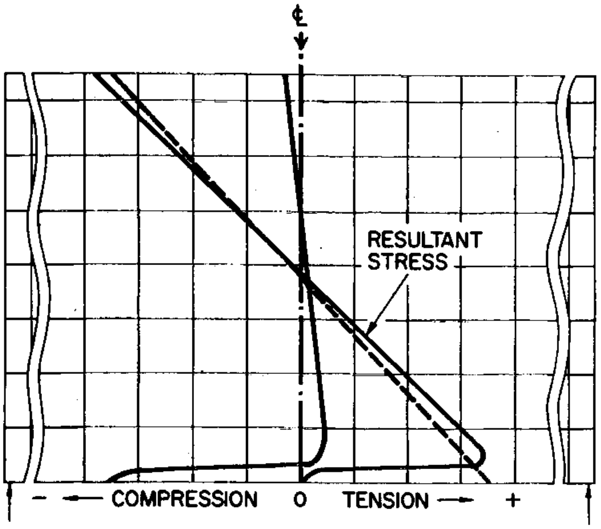

Fig. B-3 - Resultant stress—algebraic sum

Fig. B-1, the resultant stress will be the algebraic sum of the residual and applied stresses at any depth, as shown in Fig. B-3. In this particular illustration, the maximum applied tensile stress is equal to the residual compressive stress at the surface, and, consequently, the resultant stress at the surface is zero. At the depth where the residual stress curve crosses the zero line, the resultant stress is exactly equal to the applied stress at that depth. It is beyond this depth that the residual tensile stress becomes additive to the applied tensile stress, and therefore the significance of the slope of the residual stress curve in this region is apparent. Note in Fig. B-3 that the maximum resultant tensile stress occurs at a depth just slightly greater than that zero point. Note also that the magnitude of this maximum stress is less than that of the applied tensile stress at the surface. But the gain in fatigue strength is likely to be considerably greater than indicated by this difference, because of the fact that the surface is more vulnerable to fatigue failure than subsurface material (7).

This brings us to the crux of the problem. In the particular case shown in Fig. B-3, the resultant maximum tensile stress is zero at the surface, and therefore failure at that surface is extremely unlikely. If, in fact, failure does occur, it is most likely to start at the point of maximum resultant stress. It is not practical at this point to determine a relationship between the fatigue strength of the surface and that below the surface, but in this particular case, it seems evident that surface failure is out of the question.

However, if the maximum residual compressive stress in the peened beam had been below the surface, and the surface compressive stress appreciably less, it is conceivable that the ratio of fatigue strength (surface to subsurface) could be such that failure might be initiated at either location. In this connection, consider the example in the text for reverse bending at the surface. In that instance, there was an increase of more than 100% in endurance limit stress, in spite of a substantial reduction of surface residual stress in the first few cycles. This suggests that since no failure occurred at 52,000 psi, the residual compressive stress at the surface was sufficient to reduce the resultant stress to a magnitude less than the endurance limit of that surface. Here, again, we are faced with qualitative comparisons, but assuming validity to this point, we have reduced the probable nucleus of failure to two points (surface or position of maximum resultant tensile stress).

It will be noted that, up to this point, any change in physical properties of the material by shot peening has been ignored. This simply means a conservative approach. Shot peening has long been recognized as a means of work-hardening certain materials. Any work-hardening that does occur is the result of cold work or plastic deformation due to the impact of the shot. But any such plastic flow is the source of the residual compressive stress resulting from peening; therefore, the increase in hardness and residual compressive stress will be coincidental. Thus, it appears unlikely that an increase in hardness will have a significant influence upon the overall results of peening.

On the basis of a larger number of residual stress measurements (6), the magnitude of the maximum compressive stress after peening is a function of the material peened rather than of the conditions involved in the peening operation, assuming that adequate coverage is achieved.

In softer steel, the magnitude of the maximum compressive stress was substantially equal to the yield strength of the material. At a hardness of 50 Rc, it was more nearly 60% of yield and was less likely to occur at the surface.

Due to the fact that the measurement of the residual stress distribution involves the successive removal of layers of the metal and taking measurements at each depth, it is time-consuming and expensive. For this reason, it is not practical to use such measurements as a direct production control. Add to this the fact that the actual distribution of the residual stress resulting from identical peening conditions may be different for different shapes or even for different thicknesses in the same shape, and it becomes evident that the analysis of the distribution and its influence upon fatigue strength becomes quite complex on any quantitative basis. But long experience in peening has convinced the author that an understanding of the characteristics of such stresses would result in a complete reappraisal of the potential possibilities of the process.

A realistic approach to the problem might well be one in which an attempt is made to consider the fundamental factors involved and to get them to add up, even on a qualitative basis. This requires care in avoiding snap judgment, as well as a great deal of effort to make sure that any such relationships that might appear to exist are valid, and not applicable only to the conditions under which the analysis is made.

Even though we are limited to qualitative interpretation of measured results, we can set up certain limits within which a fundamental concept appears valid. With this in mind, a few obvious facts can be established:

1. The summation of all forces within an integral component, or piece of metal with no externally applied load, must be zero.

2. The summation of the moments of these forces about any point must be zero. In a simple rectangular cross section, it is relatively easy to visualize the balance of the forces and moments. But, regardless of the complexity of a particular shape, there must be a balance.

3. Any residual compressive stress at or near the surface of a part cannot exist unless it is accompanied by a balancing residual tensile stress somewhere in the part. The significance of the tensile stress in its influence upon fatigue strength of the part will depend upon its magnitude and location in relation to the distribution of the applied stress during the use of the part. (In a thick cross section, it might be of no significance.)

4. When an external load is applied to a peened component, the resultant stress at any depth is an algebraic sum of the residual stress and the applied stress at that depth, using the conventional concept that tensile stresses are positive and compressive stresses are negative.

Based on the above statements, the following theory is presented: if the maximum resultant stress at any point in a component exceeds the fatigue strength of the material at that point, failure is likely to occur, starting at that point. If the resultant stress does not exceed the fatigue strength of the material at any point in that component, failure is not likely to occur.

Note that this theory makes no reference to ultimate strength, yield strength, or any other property of the material except its fatigue strength. By implication, this means that if the applied stress exceeds the yield strength of the material, or even its ultimate strength, it does not mean that failure will necessarily occur in the component. If a residual stress distribution could be obtained that would oppose the applied stress at every point in the critical cross section of the component to the extent that at no point would the resultant stress exceed the fatigue strength of the material at that point, failure could not occur, regardless of the magnitude of the applied stress.

This theory recognizes the fact that the fatigue strength of a surface is likely to be appreciably less than that of the subsurface material, even under the most favorable conditions of the surface (7).

Admittedly, this theory, in its application to a practical problem, must be considered on the basis of qualitative valves, because of the lack of quantitative measurements. But even so, it can be extremely useful in pointing the way to achieving results far superior to those which could be obtained in its absence.

In support of this theory, consider the effects of stress peening (8). It has been demonstrated that the fatigue strength can be enormously increased by simply shot peening a leaf spring, while an external bending load is applied to the spring in the same direction as that of the applied stress to be sustained in service. This procedure is compared in terms of fatigue strength to identically peened specimens, except without the applied stress during peening. The difference made by the use of the applied stress during peening greatly exceeded that between peened and nonpeened specimens. At first glance, it might appear that the reason for this influence is the fact that the magnitude of the compressive stress at the peened surface is greatly increased by the release of the applied stress after peening. However, even on a conventionally peened beam, the magnitude of the compressive stress at the surface is sufficiently high that the resultant stress is likely to be well below the endurance limit of the nonpeened specimens.

It is far more conceivable to believe that the removal of the bending moment after peening is equivalent to adding a bending moment to the residual stress distribution, which moment is in exactly the opposite sense as the relationship of the applied bending stess in service. Thus, a compressive stress is added to the ordinary residual stress distribution in the "ideal" sense, to provide a far more favorable distribution of residual stresses.

Unfortunately, stress peening is limited in its application by several factors. It cannot be used in the case of complete reversal of applied stress for the obvious reason that the bending moment during peening can be applied in one direction only. In complex shapes, such as gears, no practical means has been found to subject the tooth to a bending moment during the peening operation. Stress peening has been used in automotive production of leaf springs with exceptionally impressive results. This is a clear-cut case of stress peening in design, since the number of leaves in the spring assembly was drastically reduced (to one leaf). It can be used also in coil springs or other applications involving torsion in one direction, because of the similarity of the applied torsional stress distribution to that of bending. It is similarly limited to torsion in one direction only, as in the case of bending.

Fundamentally, stress peening approaches the "ideal" distribution of residual stress, and this is demonstrated by the gross increase in fatigue strength beyond that obtained without the benefit of the "released bending moment."

Further support for this theory is given by the fact that many spring manufacturers have used presetting after shot peening, and obtained an added gain in fatigue strength thereby. This process is known as bulldozing, scragging, etc., and consists of subjecting the peened spring to an overload in the same direction as the service load. This load is sufficient to cause some plastic deformation as evidenced by a permanent set after the load is removed.

This added fatigue strength would be expected if we refer to Fig. B-3 and assume the bending stress to be greater than that shown. It will be apparent that the maximum resultant stress will occur at the surface under compression (top of Fig. B-3) or just slightly deeper than the point of zero residual stress. In the present case, we are dealing with static stresses and need be concerned only with yield strength of the spring. Obviously, yield will first occur where the resultant stress first exceeds the yield strength. If it occurs on the compression side, it would seem of little consequence, because even if some yield should occur here, thereby setting up a residual tensile stress, fatigue failure is not likely on the compression side. But yield on the tension side will occur in just the region where the maximum resultant tensile stress occurs in service. Such yield, provided it is moderate, will place a compressive stress automatically located in just the proper place. Excessive yield is avoided in such a presetting operation, because it may result in loss of the added benefit, and even a partial loss of that obtained by peening only. A theoretical analysis using a distribution curve similar to that of Fig. B-3 further agrees with experience in that if major yield occurs, the distribution of the residual stress is adversely affected.

To avoid confusion, it should be mentioned that the gain afforded by presetting does not approach that of stress peening.

Stress peening has been mentioned primarily as a means of demonstrating the concept of the distribution of the residual stresses, and the value of considering not only the residual compressive stress at the surface, but also the distribution of the residual stress pattern. This is the same as saying that if the failure is most likely to start at the surface even after peening, it is of prime importance to provide a sufficiently high magnitude of compression, at that surface. If, on the other hand, the magnitude of the residual compressive stress at the surface is adequate to prevent failure there, it will be just as futile to attempt to increase further the allowable stress on the component by further increasing the surface compression as it would be to increase the size of the largest and strongest link in a chain that is subject to failure. As a matter of fact, it could be even worse. In the case of the chain, increasing the strength of the strongest link may have no effect on the strength of the chain. But, in a limited thickness, an increase in the area under the compressive part of the curve, by increasing the magnitude or depth of the residual compressive stress, could lead to a diminished gain by virtue of the fact that the maximum resultant stress may be greater. Any increase in the compressive area will increase the residual tensile stress necessary to balance it. This is an example of the earlier statement that, even on a qualitative basis, an examination of the factors involved can be of great help in pointing the direction to a more effective solution. That is, in this case, we may not know the exact distribution of the residual stress in a given peening application, but if we can establish, by some means, that the magnitude of the compressive stress at the surface is adequate to prevent failure there, then we know that there is nothing to gain by increasing it, and there may be some sacrifice by so doing. If we cannot achieve further gain by increasing the magnitude of the surface stress due to peening, and we recognize this limitation, then we can examine the problem to determine what we can do to reduce the maximum resultant tensile stress in relation to the fatigue strength of the material at the point where it occurs.

It must be recognized that, before we are in a position to utilize all of the potential advantages of shot peening, we must have a great deal more knowledge of the characteristics of the residual stress patterns resulting from peening than we do today. But, before solving a problem, we must first define it. This is an attempt to do just that. As cited in the beginning of this discussion, the process has been developed to the point that even without the assurance that we can reap the full advantage potentially available, shot peening can be very effective in increasing fatigue strength, to be used in the most fitting and profitable manner under the present state-of-the-art. The term "art" is used here in the full impact of the word. We can call it a science, but with today's information, such nomenclature is necessarily extremely loose.

Finally, it seems rather evident that, if the surface is the only source of fatigue failure, even in the shot-peened condition, then it would follow that the only requirement in peening would be a high compressive stress at the surface, and the depth of the compressively stressed layer would be of no significance, except for the caution that might be taken to ensure against warpage in very thin material. But even this concept would be somewhat redundant, because if the surface is the sole criterion, then it would be perfectly logical to choose a condition for peening the thinnest part. If a high compressive stress is imposed on that thickness, then it would be necessary only to obtain the same surface condition for all parts regardless of size.

This is quite contrary to the author's experience, and also contrary to the results of fatigue tests by other investigators. A specific example is a series of tests in simple bending on cantilever beams of spring hardness (40-45 Rc). The specimens were 1/4 in thick and 1 in wide in the most highly stressed section. As the arc height was increased from a relatively low value, the life to failure increased, but only to an arc height of about 0.014 A. Above that value, still using substantially the same coverage, no further benefit was obtained, even at arc heights equivalent to more than double that figure (9).

In contrast to this series of tests, on sections 1 in thick, a moderate gain was obtained at an arc height that, in 1/4 in thick specimens, gave the best results. But, as the arc height was increased above that value, the life to failure increased, even at an accelerated rate, up to and including the highest arc height that could be obtained. To be specific, the highest arc height tested in this series was 0.015 C as measured on the original No. 1 Almen gage, which indicated only the longitudinal arc height. An estimated comparison would be equivalent to about 0.085 A as measured on the current gage (9).

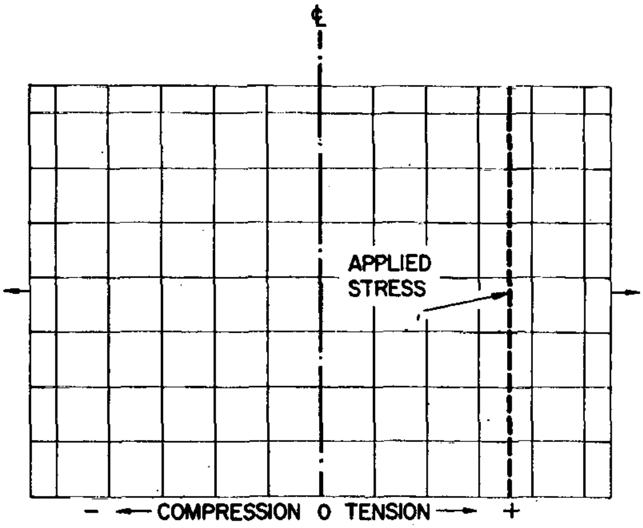

Fig. B-4 - Applied axial tensile stress

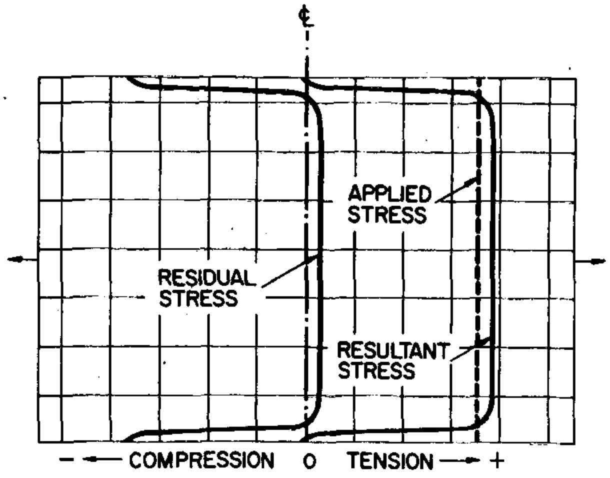

Fig. B-5 - Residual stress—peened both sides (left) resultant of residual and applied tensile stress (right)

When considering the foregoing discussion, it becomes apparent that if this reasoning is correct, it is of considerable importance to choose peening conditions best suited for the particular application, fully realizing that this choice of necessity is guided by experience, judgment, and whatever emperical relationships may have been gleaned from fatigue tests on specimens and/or parts, peened under a variety of conditions.

If we are to make an intelligent choice, we must recognize that the selection of the peening conditions should be made in the light of the size, shape, and hardness of the component to be peened, the type of loading to be encountered in service, the life requirements, and the economics involved in the production of the part. These conditions should be chosen in relation to known measurements on a quantitative basis insofar as possible, and in accordance with any qualitative yardsticks that might be available, if we expect to obtain the maximum utilization of known characteristics of peening at the least cost. Not that the process is an expensive one. In an automotive application, it is probably in the category of a moderate cost operation. But, in the majority of such applications, the process is likely to be one adopted for the express purpose of reducing the overall production cost of the component. In such a case, it is only logical to select and control the peening conditions in such a way that any unnecessary cost is pared from the operation.

In the light of these variables, the question might well be asked, even on a current production process, whether it is being used to best advantage. The impact of shot on the surface is likely to result in a beneficial compressive residual stress at the surface, even under adverse conditions. A careful look at peening conditions might reveal a possibility of reducing cost of the operation with no sacrifice of quality.

On the basis of this reasoning, it would be expected that in applications involving pure axial tensile stress, the gain in fatigue strength would be less than that obtained with the gradient of applied stress in bending or torsion.

Considering a simple rectangular bar as shown in Fig. B-1, if the applied stress were pure tensile, its distribution through the cross section would be represented by a vertical line shown in the dotted line in Fig. B-4; that is, the same in all points of the cross section. Quite obviously, in such a case, it would be necessary to peen all sides of the bar if any gain is to be had. Using a peening condition similar to that of Fig. B-1, the residual stress distribution would be somewhat as shown in the solid line to the left of Fig. B-5, when peened on both sides. Note that the magnitude of the maximum residual tensile stress is appreciably less than that for Fig. B-3, and also that the residual tensile stress is at a constant level between the two zones of compressive stress. Note also the symmetry about the centroid of the thickness, which means that if the areas in tension and compression (forces) balance, the moments will automatically balance.

The significance of Fig. B-5, however, is the fact that the maximum resultant stress will be unquestionably of a greater magnitude than that of the unpeened bar. However, as mentioned earlier, the fatigue strength of even a well-finished surface is less than that of subsurface material; therefore, the fact that the resultant tensile stress at that vulnerable surface has been drastically reduced would indicate no surface failure. This leads to the conclusion that a gain will be obtained even in this type of loading, but in the absense of a gradient of applied stress, the relationship of peening conditions to thickness would be different than in the case of bending or torsion. The degree of gain is now dependent upon the relationship of the fatigue strength of the subsurface material as compared to that of the surface. This, again, is subject to a qualitative appraisal, and we would expect it to be influenced by the qualities of the surface that influence its fatigue strength, such as roughness or other forms of stress concentration, notch sensitivity, etc.

In any case, two conditions seem to be implied. The magnitude of gain is likely to be less than in the case of bending, and the depth of the residual compressive stress is likely to be less significant than in the case of bending. On the basis of the resultant stress, we would expect that in pure axial tension surface protection is the vital factor, and a shallow depth of compressive stress is all that is necessary. In other words, with good coverage to assure the presence of an appreciable compressive stress on the entire surface subjected to that axial stress, a low impact should be adequate, or even desirable.

Whereas in a very thick part, the stress gradient in bending could be so flat as to approach axial stress, its occurrence in automotive parts seems unlikely, even in cases apparently involving purely axial loads. The difficulties so often encountered in the laboratory in eliminating unwanted side loads, inertial loads, etc., suggest caution in assuming purely axial loading in components in service.

On the basis of limited data, there appears to be an indication of real gain in axial loading, but of less magnitude than in bending.

APPENDIX C
"WEAKEST SPOT" THEORY

In a section in the text, it was mentioned, in relation to thin parts, that the gain in life continued to increase with coverage, even well beyond 98%, provided the arc height was not excessive for the thickness of the part. In the region of very low coverage, this is not surprising. But at values well beyond 98%, there seems to be no obvious explanation. In fact, it was not until a great deal of data had indicated such a positive trend that it was taken seriously. In attempting to explain the trend, the only plausible theory not easily disproved was based upon the premise that failure starts at the weakest point. That attempt at an explanation follows.

In Fig. C-1, the horizontal line at the top represents the original surface, and the solid curved line below it depicts the assumed profile of the depth of the compressively stressed layer resulting from a very sparse coverage. The indentations of two impacts are shown as two solid arcs adjacent to the surface. Note the assumption of compressive stress between the indentations. The supporting evidence of its existence lies in the fact that in fatigue tests, specimens peened with a coverage of only 30% showed a clear increase in life from 50,000 to 125,000 cycles (average). These tests are shown in Fig. C-2. Obviously, this means that 70% of the area was not touched by the blast. But if that area had not experienced some improvement, the life of the specimens would not have been increased at all.

Thus, it is assumed that there is a compressive stress in the entire critical surface, but at some point that stress extends to a minimum depth. That point has experienced the least gain and therefore is the weakest point.

The dotted indentation, and the curved dotted line below in Fig. C-1, represent the condition after additional coverage is obtained by a second pass in the same region, simplified somewhat by locating the added impact midway between the first two.

At this point, it is assumed that, provided the impact of the shot is not excessive for the thickness of the part, the life depends upon the depth of the residual compressive stress at the weakest point.

On the basis of these assumptions, the weakest point will be strengthened by increased depth due to the impact of the third pellet (dotted indentation). The minimum depth will then be at a point between two adjacent indentations (minimum depth on the dotted line), at which the depth has been increased, but not to the depth now occurring directly below an indentation.

Thus far, the theory is in keeping with the results of further

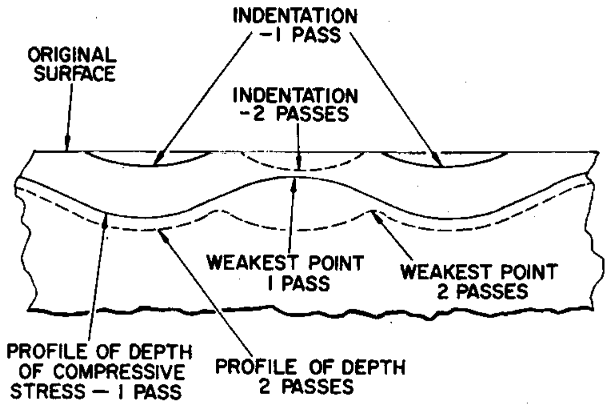

Fig. C-1 - Profile of peened surface

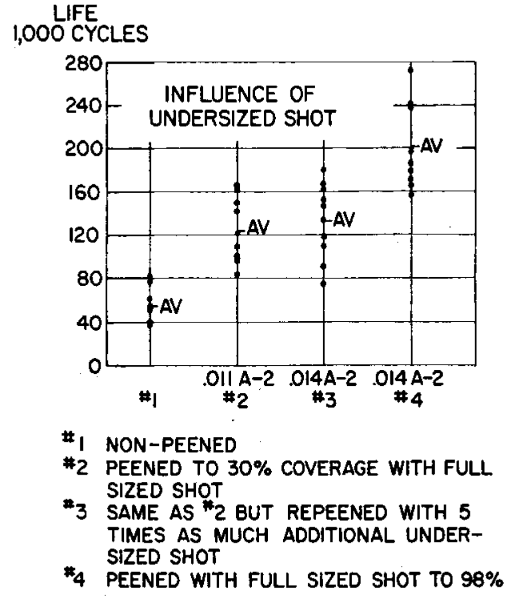

Fig. C-2 - Tests using undersized shot

tests, in which the life of specimens, peened at a low enough arc height to avoid excessive depth, increased as the coverage was increased above 30%. For example, refer to the test shown at the right of Fig. C-2, peened at 98% coverage, using full-sized shot. Here, the life has been increased clearly beyond that at 30% coverage.

Additional tests with increasing degrees of coverage, at an arc height of 0.014 A, showed progressively increased life, well beyond a coverage of 98%. Referring again to Fig. C-1, and the asymptotic nature of the coverage curve of Fig. 4, 100% coverage is approached as a limit, and small regions of the surface will be struck at random, many areas being hit repeatedly, and others being just missed.

In this manner, it can be visualized that the maximum depth will be obtained when the last "bear spot" is hit. At that time, it would be expected that, if this theory is correct, the curve of life versus coverage should level off. But this is at an indeterminate time because of the asymptotic nature of the curve.

Two questions now remain. Fig. C-2 shows no significant change in life when specimens, previously peened with only 30% coverage using full-sized shot, are then peened with five times as much undersized shot, even though the arc height was increased (without exceeding the optimum), and the coverage was grossly increased. Why is the life not increased? It will be recalled that this additional peening was done with undersized shot, simulating that resulting from shot breaking down in a machine. The reduced mass of these pellets, it is believed, is entirely capable, in the region of 30% coverage, of increasing the arc height of an Almen specimen, by virtue of the superficial expansion of its surface, without actually increasing the minimum depth of compressive stress.

The second question deals with arc height. If the life of the part being peened is a function of the minimum depth of residual compressive stress, then why not simply use a higher impact, or specify a higher arc height? According to the concept given earlier, that when the impact has exceeded the value at which subsurface residual tensile stress becomes the determining factor, an increase in arc height will not result in increased gain. This was further illustrated by additional tests in which fatigue specimens 1/4 in thick were peened with multiple coverage but at an arc height well above the optimum. With this high arc height, there was no advantage whatever at the multiple coverage; that is, the life was substantially the same as that for 98% coverage. If the depth is excessive, then increasing it is of no value. It will increase the subsurface tensile stress, which is already too high.

Unfortunately, there is no known means of appraising this theory by measurements of residual stress. In order to measure the residual stress below the surface, it is necessary to remove layers from the surface. This removes all of the stresses in a given layer, and therefore their influence on any measurement represents an average and tells us nothing about the lateral distribution of stress depth involved in Fig. C-1.

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