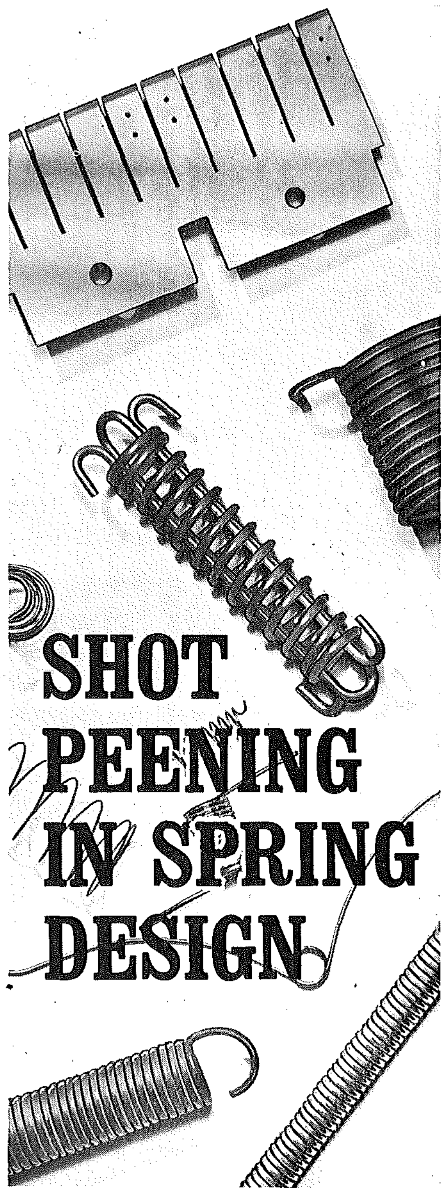
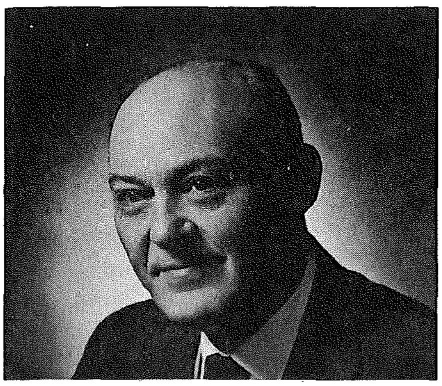


SHOT PEENING IN SPRING DESIGN



By
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INTRODUCTION

Shot Peening is a process utilizing the impact of metallic shot on the surface of machine parts. While in general, there are other purposes of shot peening, its major purpose is increased fatigue strength of components which are subject to failure due to repetitive applications of stress.

It has been used for many years for the purpose of preventing the recurrence of failure in a particular design. Presumably for that reason, the process is often referred to as one which can provide an increase of 200% or 300% in life. However, this is far short of the available gain in fatigue strength by this process.

It is my firm belief that the available gain in fatigue strength is great enough that it can be used not only to eliminate failures in an existing design, but also to increase the working stresses, thereby permitting an attractive reduction in the size and weight of the part. This is particularly true in springs in which a large proportion of the spring is subjected to high working stresses. In volume production, this can result in an attractive reduction of the cost of manufacturing springs. In addition to the saving in weight as such, there are those applications in which the reduction of an assembly is limited by the space that can accommodate a spring which may be a vital part of the assembly.

HOW MUCH INCREASE IN FATIGUE STRENGTH?

The degree of increase in fatigue strength in a given application will depend upon a number of factors. Therefore, it is not feasible to generalize on the amount of increase that is available.

A few examples might serve to give some idea of the results obtained in specific instances. In one instance, coil springs showed an increase of 2,000% in life; in another 5,500% increase in life. On a leaf spring, in one case, 600% increase and in another 1,200%. In still another case, the endurance limit stress for leaf springs was increased over 50%. These are simply examples of particular tests, and the comparison is not intended to imply that one type of spring is subject to a greater increase in life than another type.

Some concept of the possibility of saving spring steel can be obtained from a production operation for peening chassis coil springs. Assuming only a 10% increase in stress, a reduction in the weight of the spring would be about 20%, assuming a reduction in the wire diameter and a reduction in overall length to obtain the same spring rate. On the basis of the output of a production machine, this would amount to a saving of approximately 1900 pounds of spring steel per hour.

Figure 1 shows an SN diagram for a particular series of tests on leaf spring specimens. The specimens had a thickness of 1/4″ and were tested at a range of substantially zero to maximum bending stress. It will be noted that the two lines are not parallel, but converge toward the lower number of cycles. This means that the amount of gain is influenced by the magnitude of the applied stress for a given peening condition. In many cases, it is difficult to measure a precise value of the applied stress, in which case the non-peened life can be taken as a criterion. Consider a point at about 1/2 million cycles on the non-peened line. At that life, the stress is increased by about 34% by shot peening. Starting at the same point, the increase in life is indefinitely large because the stress is below the endurance limit stress for this particular peening condition.

Figure 2 shows in a qualitative manner the influence of peening conditions on the SN diagram. The upper dotted line indicates a more effective peening condition than the solid line. This could be due to a difference in choice of peening conditions (the lower line may be entirely adequate for the specific application) or to a difference in the degree of control of the peening operation. As will be seen later, the choice of peening conditions and the degree of control of the operation can have a decided influence on the location of the SN diagram after peening. In the final analysis, a peening condition should be chosen in relation to the requirements so that these requirements can be fully met at the minimum cost.

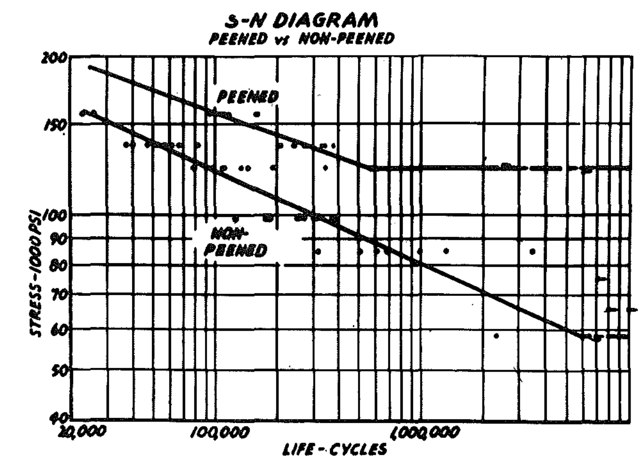


Figure 1

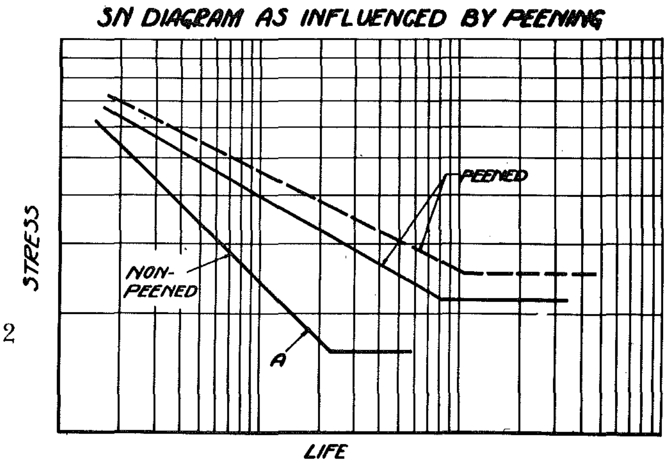


Figure 2

In addition to the variables mentioned, the gain in fatigue strength of a particular part may be strongly influenced by the condition of the part before peening. For example, there may be residual tension stresses in the non-peened part which would reduce its fatigue strength. Since such stresses are eliminated by shot peening, the gain in such a part would be greater (and possibly much greater) than if the part had been stress-free before peening. A similar comparison could be obtained with a different surface roughness. A rough surface could penalize the life of a non-peened spring, but have little or no influence on its life after peening.

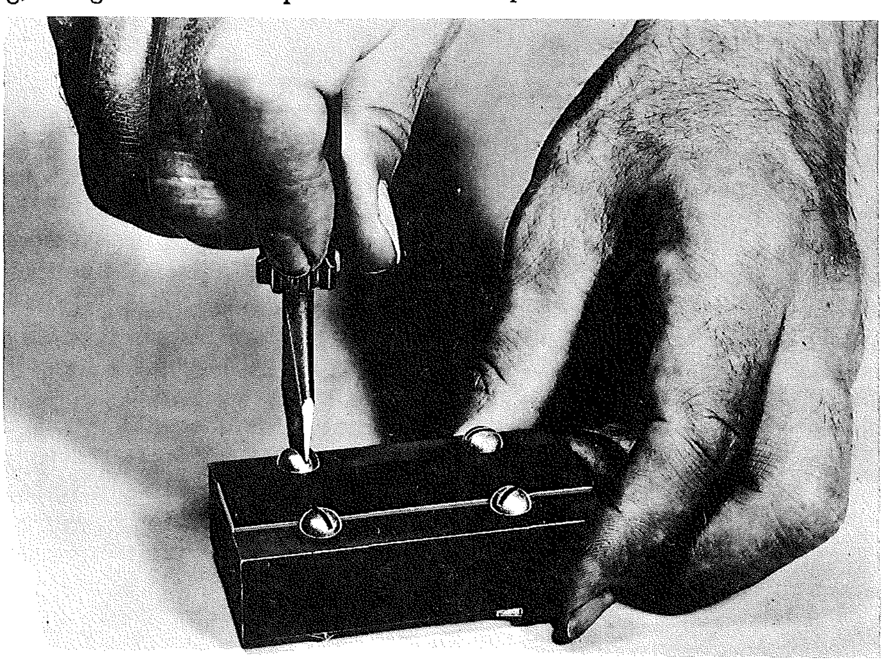
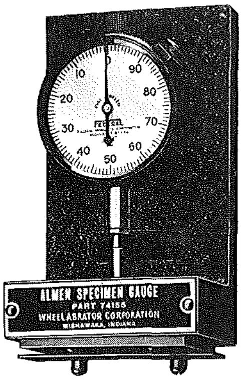


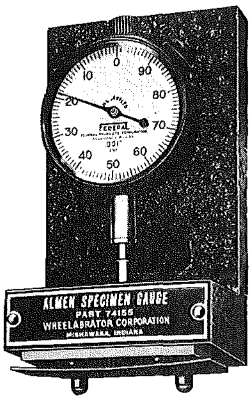
Figure 3

It will be apparent from the above discussion that if fatigue tests are made to appraise the value of peening in a particular application, it is important to obtain a life to failure on the non-peened part which is comparable to its life in service. If the test load is increased to accelerate the fatigue test, we would expect less gain than that at the normal service load. It is also important to obtain failures in laboratory tests on the non-peened part which duplicate, as nearly as practical, the failure in service.

PEENING SPECIFICATIONS

Specifications for a peening operation should include arc height and coverage. Figure 3 shows an Almen





specimen being mounted on a standard holding block. The specimen itself is a strip of spring steel, ¾″ wide and 3″ long with a hardness of 44 to 50 R_C, and flat within .001″ as measured on the standard Almen gauge. These strips are available in 3 standard thicknesses: the N strip, .031″; the A strip, .051″; and the C strip, .094″ (plus or minus .001 in each case). The thinner strips are for low impact peening.

Figure 4 shows a standard Almen gauge for measuring the curvature of the strip after peening, in terms of arc height. The specimen, attached to the block, is exposed to the blast in the same cycle as the work to be peened. This results in a curvature, convex on the peened side, as shown in the right hand photograph. The gauge registers .019 arc height. Since the strip measured is an A strip, this would be referred to as an arc height of .019A. Higher arc heights indicate greater depth of residual compressive stress resulting from the blast of shot.

Figure 5 shows a typical curve of arc height versus time of exposure. The shape of this curve is influenced by the condition of the shot, the cycle in which the specimen is exposed to the blast, etc. But in all cases, the curve will level off for a given blast condition, so that additional exposure results in no increase in arc height.

Figure 6 illustrates the appearance of coverage on a polished Almen specimen. The left hand photograph shows a coverage of 55%, and that on the right, 90%. This is nothing more than the percentage of a small area which has been indented by the blast. To measure coverage, an Almen specimen is polished for a reflective finish and then subjected to the blast in a definite cycle which will produce less than full coverage.

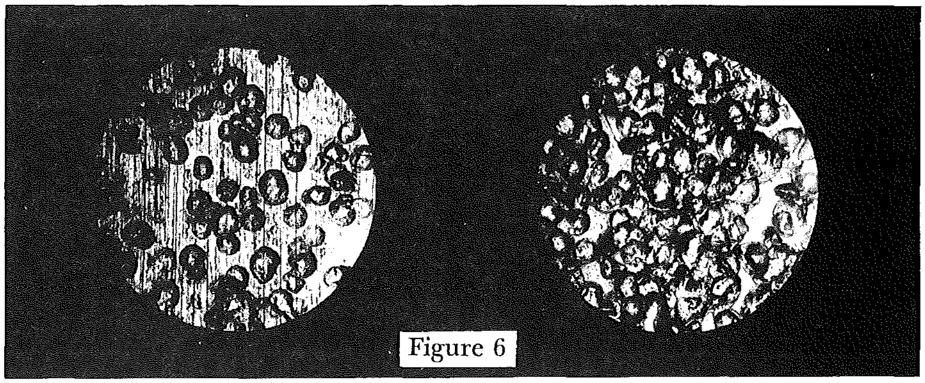


Figure 6

The polished specimen, peened to incomplete coverage is viewed in a metallurgical microscope with a magnification of about 50 to 1. The indentions are traced on a piece of transparent paper. Each indented area is connected to another area by a pencil line so that the sum of the indented areas can be measured with a planimeter in one traverse. The sum of the area of the indentations divided by the total area of the image is the coverage.

Coverage as thus described, is measured only in the setup of a peening operation. Once the desired coverage is obtained, it is a matter of controlling the blast for constant peening conditions, in conformance with the original setup.

Figure 7 shows the relationship between coverage and exposure time. Unlike the curve of arc height versus time, the shape of the coverage curve is a fixed mathematical relationship, regardless of the conditions of the blast or the cycle to which the specimen is exposed. Quite obviously, the conditions of the blast must be constant for this relationship to hold.

The relationship is:

$$C_n = 1 - (1 - C_1)^n$$

in which C = % coverage (expressed as a decimal) after N cycles through the blast

C_1 = % coverage (decimal) after 1 cycle

N = number of cycles

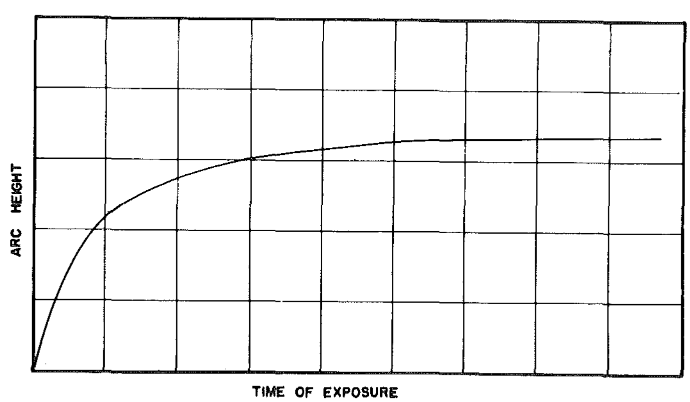


Figure 5

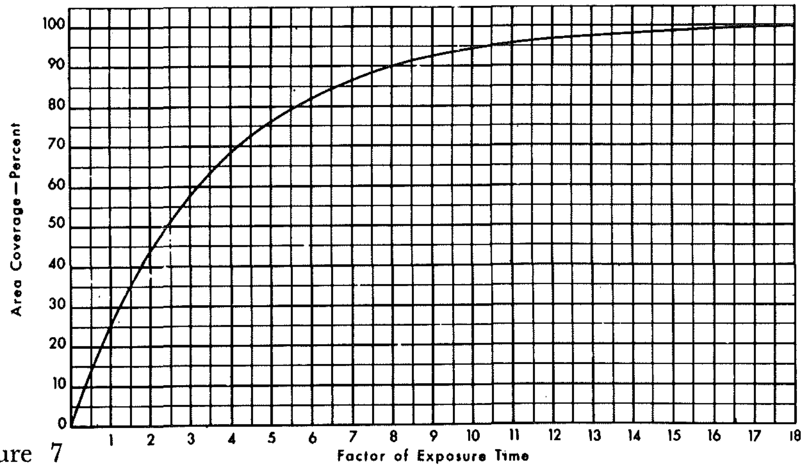


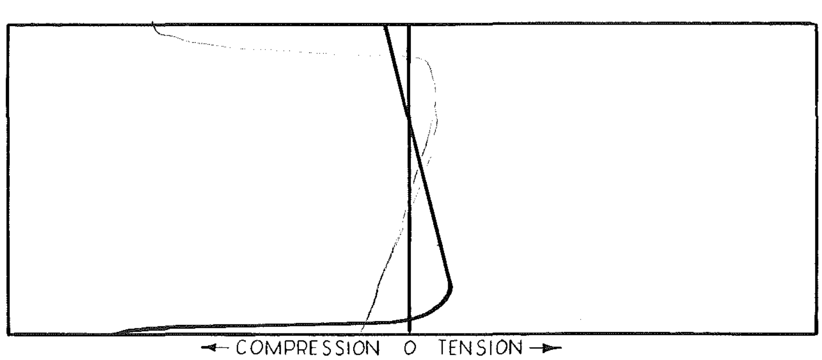
Figure 7

It will be noted that coverage approaches 100% as a limit, and therefore, the point at which 100% coverage is obtained is indeterminate. For this reason, 98% has been chosen as one unit of coverage, and beyond that point, coverage can be expressed as a multiple of the exposure time required to obtain 98%. For example, a coverage of 2 would indicate an exposure time of double that required to obtain 1 unit or 98% coverage.

WHY THE INCREASE IN FATIGUE STRENGTH?

In the early days of shot peening as a production process, several theories were advanced for the increase in fatigue strength. One such theory was that of work hardening, but fatigue tests showed gains in fatigue strength well beyond that which could be expected from work hardening. In most spring steels, for example, shot peening results in a very moderate increase in hardness. From my own experience, I am convinced that the increase in fatigue strength is primarily the result of the residual compressive stress in the surface of the material. In the absence of residual stress, fatigue failures are likely to be initiated at the surface due to applied tension stress. With a residual compressive stress in the surface, it would be expected that the magnitude of the tension stress at the surface would be reduced by this residual compression and therefore, an increase in fatigue strength would be expected. But, if the full benefit of shot peening is to be realized, it is important to consider the *distribution* of the residual stresses, as influenced by the conditions of peening, and also by the thickness of the part being peened. Figure 8 is a graphical illustration of the distribution of residual stress across the thickness of a rectangular beam after peening the bottom side. This shows a high compressive stress in the peened surface, decreasing to zero at some depth, and immediately below that point, the residual stress changes to tension. At still greater depth, the residual tension stress decreases, finally becoming residual compression on the opposite side of the beam.

Figure 8



Fundamentally, a residual stress in compression cannot exist in the surface without a balancing tension stress somewhere in the sub-surface material. Considering the stresses on a unit of width, the area enclosed by each portion of the curve represents a force. Consider the area between the curve and the line of zero stress. In the region adjacent to the peened surface, this would represent a force to the left. The area of the tension portion of the curve would represent a force to the right, and the area in compression at the top of the beam represents a force to the left. With no external forces applied to this beam, the summation of these forces must be zero for equilibrium. Also, the moments of these forces about any point must be equal to zero.

Figure 9 shows the distribution of stress due to the application of an external bending load on a similar beam or leaf spring without residual stresses. Figure 10 shows the residual stress distribution from Figure 8 and the dotted line represents the externally applied stress from Figure 9. The resultant stress distribution is represented by the solid line which is the algebraic sum of the applied and residual stresses at any depth. It will be noted that the magnitude of the maximum resultant tension stress is less than the maximum tension stress due to the applied load. More important, the maximum resultant tension stress occurs in sub-surface material which is not subject to stress concentration that normally would occur at the surface. Sub-surface material is inherently stronger than that at the surface. It will be noted also that the resultant stress at the peened surface is very low. This would explain the tremendous increase in fatigue strength obtained by shot peening. In fact, in this particular case, the resultant stress at the bottom surface is zero at the particular load applied. The fact that the resultant compressive stress has been increased on the opposite side of the beam is of no consequence because fatigue failure is not likely to occur as the result of compressive stress, even at a high magnitude.

The residual stress distribution shown in Figure 8 is based on an arc height which was considered optimum for the particular specimen thickness of 1/4″ in a series of fatigue tests.

Figure 11 is similar to Figure 10 except that the residual stress is representative of a higher arc height. The magnitude of the surface residual compression stress is the same as at the lower arc height, but in this case, the residual compression is deeper, thereby increasing the area of the curve in that region. The compressive stress on the opposite side of the beam is also greater, thereby increasing the area under the curve in that region. This means that the area under the tension curve must increase. The result is a higher magnitude of residual tension stress, so that even though residual tension stresses start to add to the bending stress at a deeper point where the bending stress is reduced, the slope of the residual tension stress curve in that region has been increased to the extent that the maximum resultant stress is not further reduced by increased depth of the residual compressive stress for this particular thickness.

A comparison of Figure 10 and Figure 11 indicates that for a given limited thickness, there is a limit to the greater gain in fatigue strength which can be obtained by increasing the arc height beyond a certain value. This suggests that for effective peening, the arc height should be in keeping with the thickness of the part being peened. For example, if the arc height represented in Figure 11 were used on a beam of greater thickness, we would expect compression curve on the peened side to be much the same as that shown, because the depth of compressive stress is dependent upon the degree of expansion of the surface layer by the impact of the shot. Therefore, with a greater thickness, the residual tension stresses would be distributed over a greater area and the magnitude of the tension stresses would be reduced. On this basis, we would expect the limiting value to occur at a greater depth with greater part thickness.

Figure 12 illustrates agreement of fatigue tests with the above analysis. These tests were made on leaf spring specimens with a thickness of 1/4″, under the same stress range. This curve indicates that the life increases with increasing arc height, up to approximately .014A after which the curve levels off. In this particular series, the life at the highest arc height is somewhat less than that at .014A. Subsequent tests under similar conditions have indicated that substantially the same life would be obtained at higher arc heights as that obtained at the optimum. The item of importance here is that for a 1/4″ thickness, an arc height in excess of

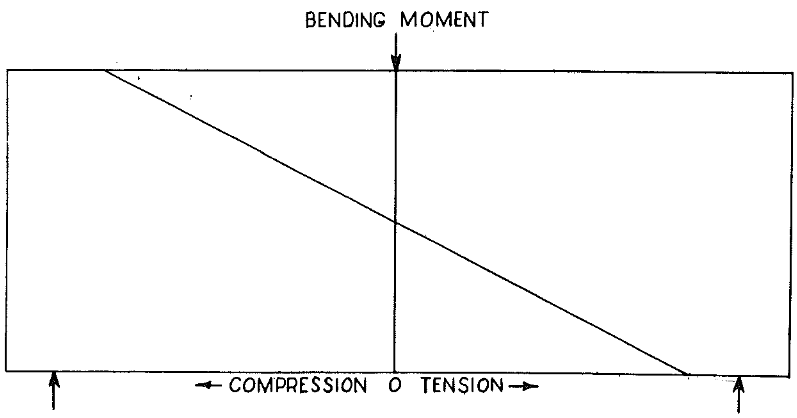


Figure 9

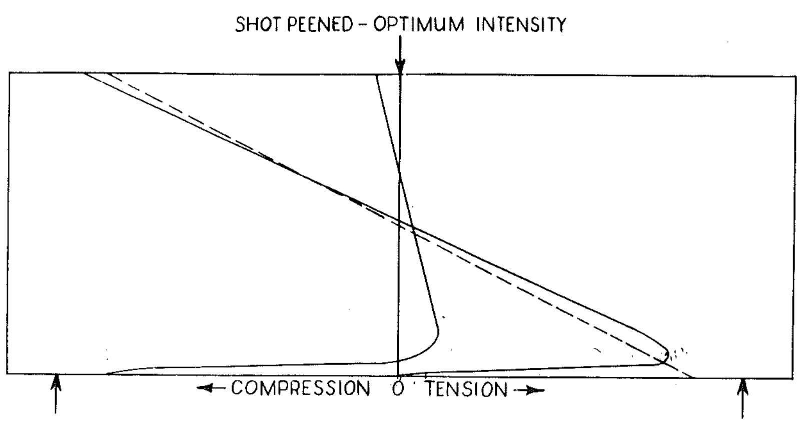


Figure 10

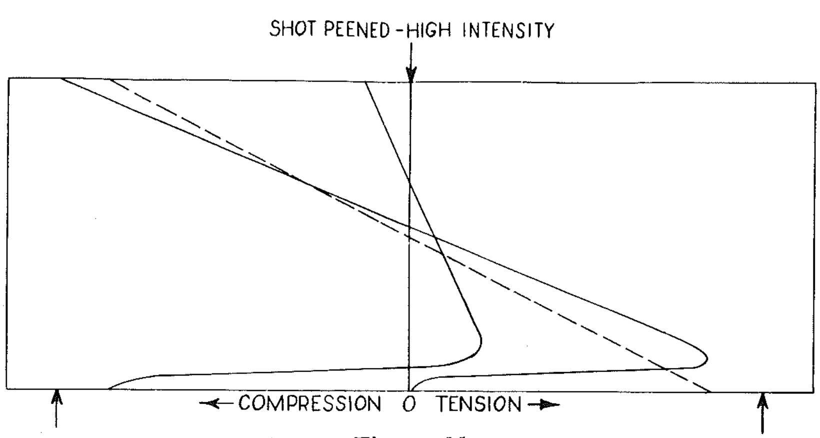
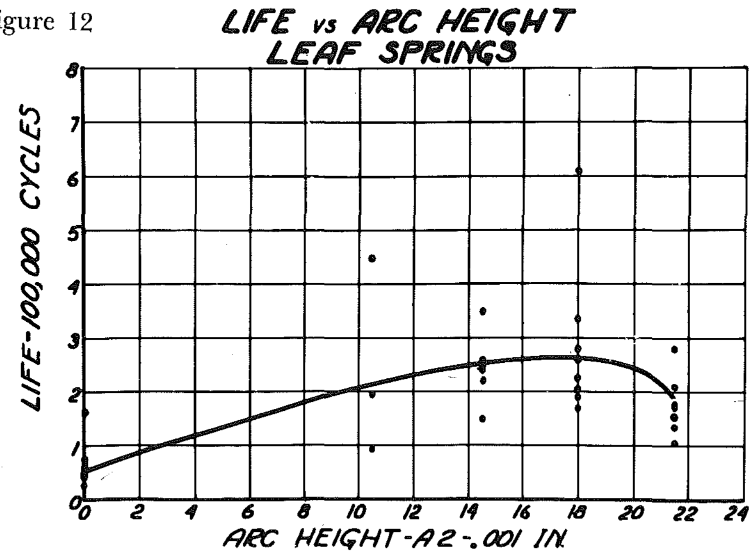


Figure 11

Figure 12



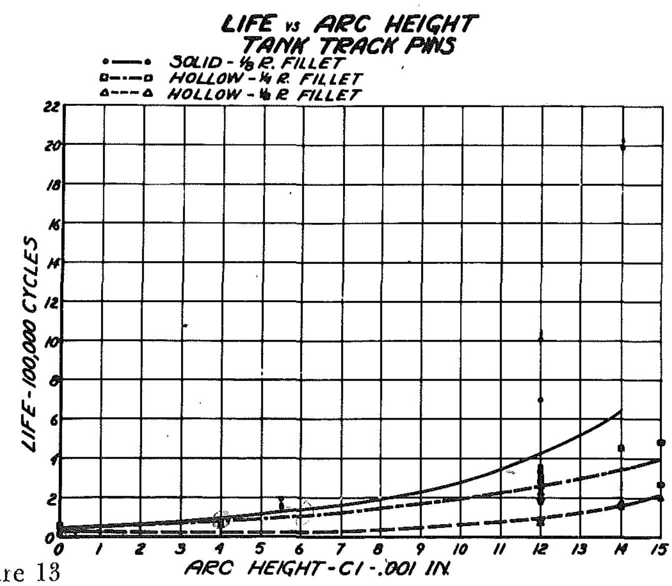


Figure 13

.014A would serve no purpose insofar as further increasing fatigue strength is concerned.

If with a greater thickness, the sub-surface residual stress in tension is truly reduced as mentioned above, then we would expect any leveling-off in the curve of life vs. arc height to occur at a higher arc height. This is borne out in Figure 13 which shows the results of series of fatigue tests in simple bending (zero to maximum stress) on tank track pins which had cross-section thickness of 1″. In this case, it will be noted that the life continues to increase with arc height, and there is no indication of leveling off, even at the highest arc height used. It should be noted that the arc heights shown in Figure 13 were measured on a standard C strip, but on a gauge measuring the longitudinal arc height only. As measured on the current standard gauge, the arc heights would be much higher than those shown in Figure 13. The track pins mentioned had a hardness in the neighborhood of 30 Rockwell C, which is lower than that of spring steel. Even so, it indicates that sub-surface residual tension stress is of much less concern when dealing with greater thicknesses, and therefore, higher arc heights can be used effectively.

Based on these and other tests, a guide has been established for arc height in relation to thickness in simple shapes as follows:

Thickness	*Arc Height*
1/16″	.012N
1/8″	.008A
1/4″	.014A
3/8″	.018A
1/2″	.021A
5/8″	.007C
3/4″	.008C
7/8″	.010C or greater

This tabulation is probably conservative, for reasons to be cited later. For complex sections, the above values are subject to modification. For example, in a tubular section the arc height can be much higher than that indicated by the wall thickness of the tube. This is indicated in Figure 13, in which some of the pins were hollow, but the curves are still rising at the highest arc height. Presumably, this is because the tension stresses are absorbed in the tube as a whole, rather than in the material immediately below the peened surface.

It should be noted that the increase in life shown in Figure 12 or Figure 13 in no way represents the gain in life to be expected under all conditions. That is, as illustrated in Figures 1 and 2, the increase in life would have been considerably greater if the life non-peened had been greater by virtue of a lower applied stress.

INFLUENCE OF COVERAGE

Additional fatigue tests have indicated that, with a given arc height, the life increases with coverage, even when the coverage is increased well beyond 98%. This is particularly true in cases involving intricate shapes, in which the angle of impact in a given area is subject to wide variations. A good illustration of this trend has been obtained on helical gears. When peened to a coverage of 98%, a number of tests have indicated a gain in stress of approximately 25% for the same life. In another case, in which gears were peened to a coverage of 7, an increase in excess of 60% in stress was obtained.

In order to achieve the advantage of multiple coverage, however, two requirements must be met. First, the arc height should not be excessive in relation to the thickness of the part. With excess arc height, an increase in coverage appreciably beyond 98% may not be effective. Presumably, this is due to the fact that the tension stress has already reached the limiting value. Second, if the applied stress approaches the yield strength of the material, multiple coverage may be ineffective. This appears to be due to the fact that a slight yielding takes place in the region of maximum resultant stress, thereby re-distributing the residual stress resulting from the peening operation. This condition is likely to occur when the life of the non-peened part is less than about 15,000 cycles.

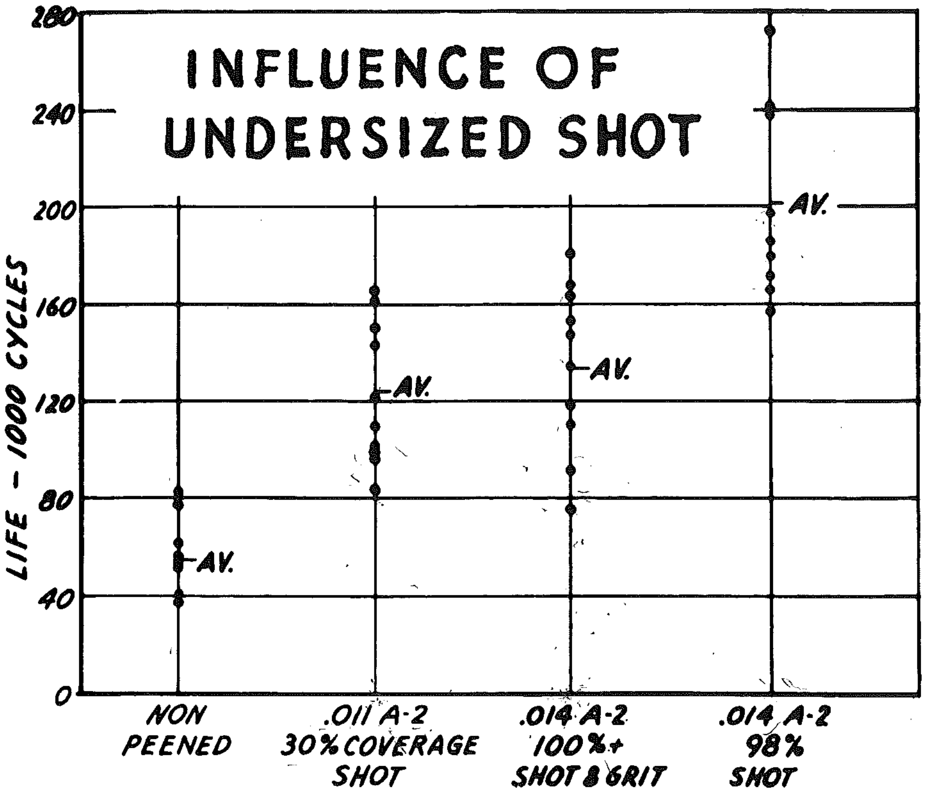


Figure 14

CONTROL OF SHOT PEENING

Inasmuch as the product of a peening machine is an increase in fatigue strength, inspection of the peened product itself is of little value. Assuming that the apparent coverage is complete, examination of the surface will not reveal the quality of the peening job. Control of a peening operation is a matter of controlling the conditions of the blast of shot.

Figure 14 shows the results of fatigue tests which illustrate the impracticability of examining the peened part for control. These tests were run to determine the influence of undersized shot. The test points at the left show an average life of about 50,000 cycles on non-peened specimens. The next group was peened with uniformly-sized shot to an arc height of .011A and a coverage of only 30%. This showed an increase of about 2½ to 1 in life. The third group was peened under the same conditions as the second group and was then re-peened with five times as much additional undersized shot, simulating the size analysis which was discovered in a production peening machine with a high percentage of undersized shot due to lack of proper separation. It is interesting to note that the life of these two groups is almost identical — in spite of the fact that six times as much shot struck the third group. Even though the coverage had been increased from 30% to over 100% and the arc height had been increased from .011A to .014A, the influence of the additional coverage with undersized shot was negligible.

The group at the right was peened to the same arc height as that in group 3 and to a coverage of 98%, with uniformly-sized shot. This resulted in almost double the average life of the second group.

The conclusion must be that if the broken or undersized shot in a peening operation is not removed, false economy results. This does not mean that one can get a better peening job by removing undersized shot. The same results can be obtained, but it will be more expensive because the work will have to be exposed a great deal longer. Therefore, the most economical operation is obtained by removing the broken shot as quickly as possible after it has been broken down.

The tests just described were made on specimens having a ¼″ thickness. In order to be certain that the lack of increased life with undersized shot was not influenced by the fact that the arc height of .011A with low coverage was rather close to the optimum arc height for that thickness, the entire test was repeated, using an arc height of .008A at 30% coverage and .011A with the mixed size. The results were very much the same in that the undersized shot produced no additional increase in life to that which had been obtained with the full-sized shot only.

It should be pointed out that the above-mentioned tests do not imply that large shot is more effective than small shot, but rather that the shot size should be uniform.

Additional tests have indicated that the current SAE specifications for shot size provide adequate uniformity for economical operation.

Because of the ineffectiveness of undersized shot, a good shot separator is essential on a peening machine for economical operation. Figure 15 shows a separator in which undersized shot is removed by a constant

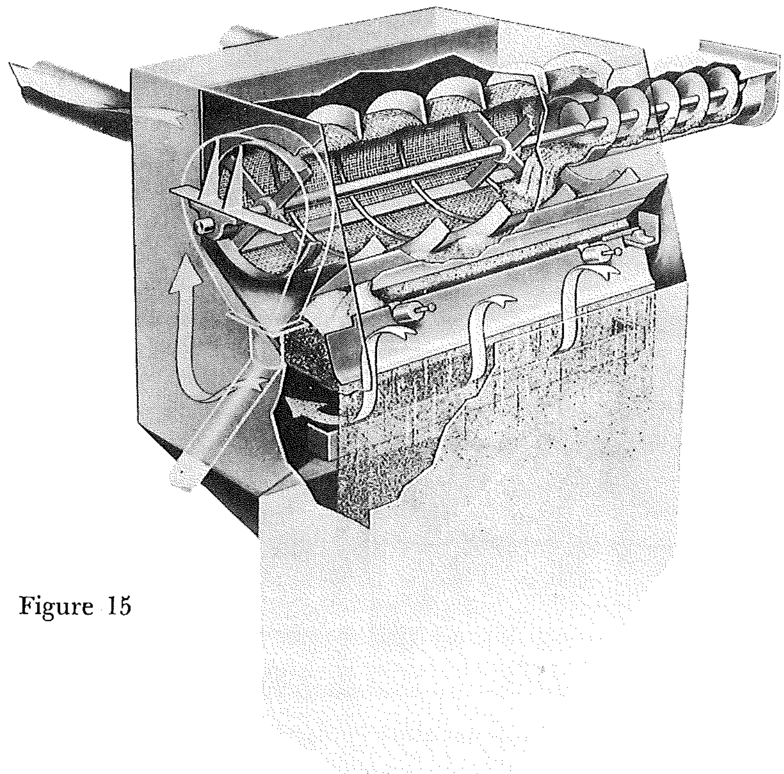
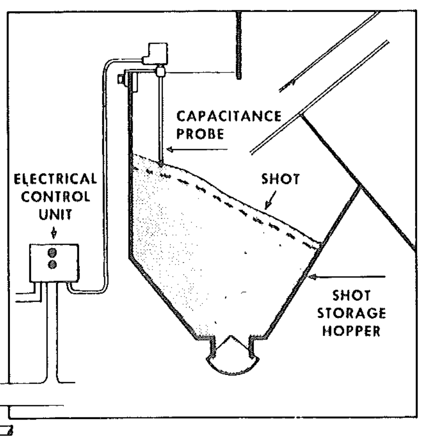


Figure 15

air stream passing through a uniformly distributed stream of shot, falling vertically at a low velocity. The shot from the elevator enters the conveyor screw, which moves it to the rotary screen for the removal of any foreign material. The shot falls through the screen to an inclined plane provided with a weighted door to obtain a uniform curtain of shot for the entire width of the separator. A constant flow of air passes through this curtain, taking out the lighter particles and allowing the heavier particles to fall into the hopper for automatic and continuous re-use of the shot.



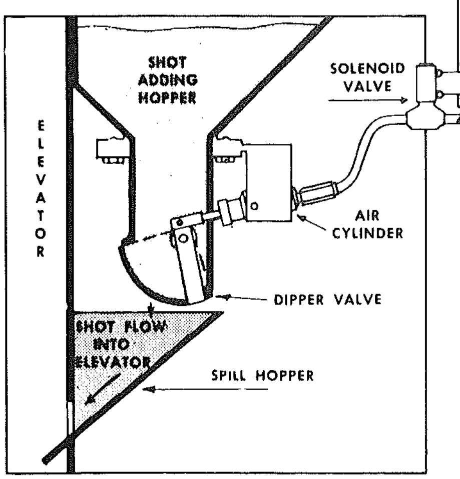


Figure 16

An automatic adding device is another essential part of a peening machine. This is illustrated in Figure 16. New shot is placed in the shot-adding hopper which is equipped with a dipper valve that automatically adds shot into the machine for makeup when the shot in the storage hopper falls below a predetermined level. When the level is restored, the addition of shot is automatically stopped.

STRESS PEENING

The foregoing discussion deals entirely with shot peening in the absence of applied stress. Probably one of the most convincing indications that residual stresses due to peening play a major role in the increase in fatigue strength is the application of stress peening.* This procedure is applicable in cases where the stress cycle does not involve reversal of stress. It consists of peening the part while it is subjected to a static stress in the same direction as the applied stress in service. After peening, the static stress is released and the gain in fatigue strength is far greater than that which can be obtained by peening in the absence of applied stress.

A similar effect, although to a lesser extent, can be obtained by presetting after peening. This may be referred to as "scragging", "bulldozing", etc. It consists of over-stressing the part after peening, in the same direction as the service stress, so that a slight yield occurs in the region of maximum stress. If such yielding is not excessive, an additional increase in fatigue strength can be obtained. This procedure also is limited to applications in which the service stress cycle does not involve reversal of stress.

EQUIPMENT FOR PEENING

In general, there are two types of equipment for propelling the shot. One type utilizes compressed air while the other type involves the use of a rotating bladed wheel. There are two types of compressed air nozzles. In the induction or suction-type, the shot is added to the air stream at the nozzle. In the direct pressure type, the shot is added under pressure to the air stream at the bottom of a pressure tank. The mixture of shot and air then passes through the hose to the nozzle, from which it is ejected. At 80 lbs. pressure, the induction nozzle is capable of delivering about 10 to 15 lbs. per minute of shot. At the same pressure, a 3/8″ diameter

* "Stress Peening" — Iron Age, pp. 66-70, April 21, 1949.

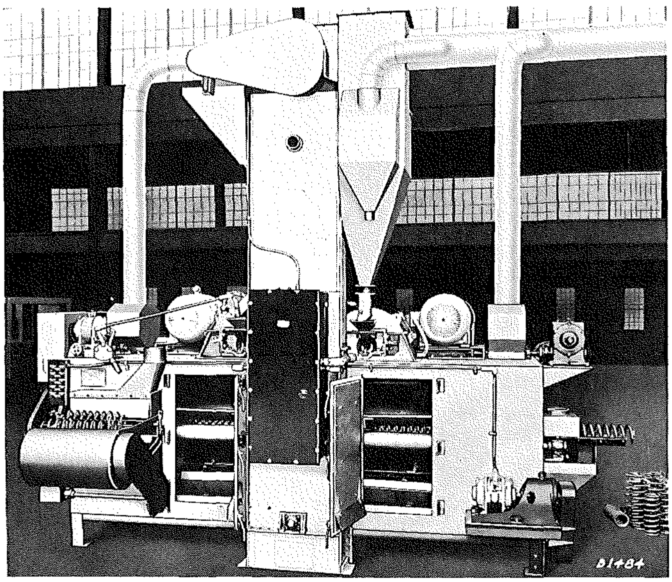


Figure 18

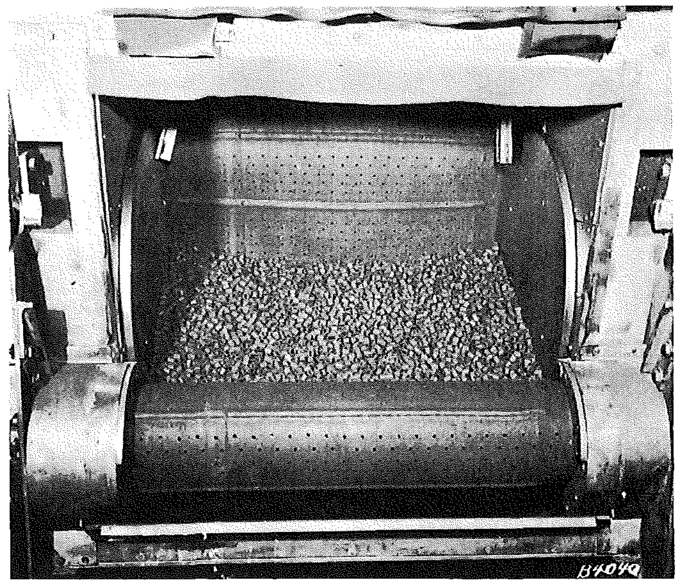


Figure 19

nozzle on a pressure tank will deliver about 60 lbs. of shot per minute.

The wheel-type equipment propels the shot by means of a rotating bladed wheel as shown in Figure 17. Directional control in this type equipment is obtained by a stationary control cage within the bladed section of the wheel. Shot from an overhead hopper is fed into the central impeller which rotates as a unit with the wheel. The shot is permitted to pass into the path of the blades

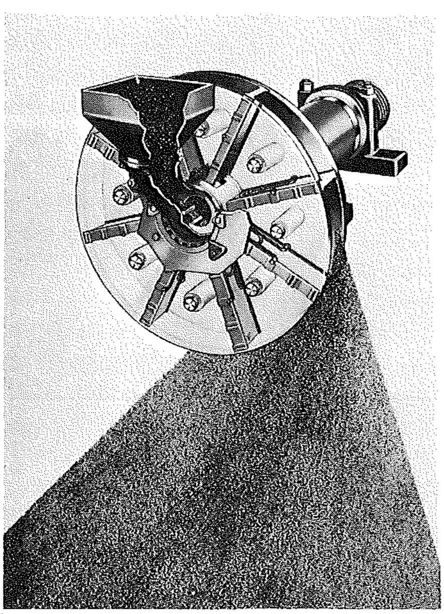


Figure 17

only through the port or opening of the control cage shown in its upper position in the illustration. At this point, the shot is picked up by the inner ends of the blades from which it is propelled in a pattern depicted in Figure 17. The position at which the shot leaves the wheel is determined by the angular adjustment of the control cage. With a power consumption of 15 H.P., this Wheelabrator unit, 19½″ in diameter, and 2½″ wide, will deliver about 340 lbs. per minute at a speed of 2250 RPM. At a 40 H.P. load, it will deliver approximately 1,000 lbs. per minute.

The equipment for a peening operation should be chosen in relation to the size and configuration of the parts to be peened, and the production requirements. For deep holes or enclosed areas, it is necessary to use an air nozzle. A nozzle is advantageous also in cases where a small area of a large part must be peened.

Where volume production is involved, it is more economical to use the wheel-type equipment because of the obvious advantage of the high shot flow rate and relatively small power requirements.

Figure 18 shows a Wheelabrator type machine for peening chassis type coil springs. This is a two-wheel unit for peening in high production.

Figure 19 shows a Wheelabrator Tumblast, which is well adapted to peening large quantities of relatively small parts such as valve springs. The Wheelabrator unit is located at the top of the mill in which the load is supported on a continuous belt which tumbles the load under the blast. This shows the front of the machine with the door open. During the blast cycle, the door is closed and the load is peened for a definite cycle. The door is then opened and the belt travel is reversed so that the belt acts as a conveyor to eject the work into a tote box. This type of machine is available in a variety of sizes and lends itself to economical operation because of the elimination of handling individual small parts.

SHOT FOR PEENING

The shot most commonly used for peening is cast steel shot. In the early days of shot peening, the only shot available was chilled iron which had a relatively short life in a peening machine. A high quality cast steel shot will last many times as long as chilled iron, and results in far less wear on peening equipment.

The broken shot which is removed by the separator in a peening machine can be used very effectively in a cleaning machine. *The End*