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SHOTPEENING EFFECTS AND SPECIFICATIONS

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SYNOPSIS

This paper briefly reviews the applications of shotpeening for strengthening and for forming metals. Current methods of specification are reviewed and analyzed. An extension of these methods is proposed to obtain "equivalent intensities" which correlate the several variables and provide more flexibility in applying the treatment. Adoption of equivalent intensities would avoid delays in the production of shotpeened parts made of various materials.

Since its beginning, about 1930, the art of shotpeening has found steadily increasing acceptance. It was first applied to automotive valve springs, then to suspension springs, axle shafts, and other highly stressed steel parts. Current applications include, in addition to such parts, nonferrous springs, carburized gears, and very substantial quantities of aluminum alloy aircraft components. In practice, the shotpeening process is carried out by propelling shot of uniform round shape and size at controlled velocity against the workpiece. Propulsion is either by a centrifugal impeller or by air blast (1).[2]

The main use of shotpeening is to increase the resistance of parts against fatigue failures. The remarkable results obtained are explained mainly by the compressive residual stress imposed on the surface of parts by peening. In the presence of this compressive stress, the surface can better withstand alternating stresses without developing fatigue cracks. In aircraft work, improved resistance against stress corrosion is also obtained by the compressive residual stresses. Hardening by cold work may also be desired and achieved. In addition, the process is used to correct the shape of parts. Slender objects such as sheets or thin shafts, peened on one side only, bend convex toward the peened side under the influence of the compressive stresses induced on that side.

SHOTPEENING SPECIFICATIONS

The general acceptance of the shotpeening process has brought about—and has been helped by—the use of standard specifications for shot and for the intensity of the shot stream (2). The specifications for shot are concerned with material, shape, and size. The specifications of the shot stream intensity are based on the measurement of residual stress effects in a standard sample—the Almen strip; by a standard instrument—the Almen gage (Fig. 1). It is well understood that the Almen intensity is only one of the variables in the peening proc-

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[2] The boldface numbers in parentheses refer to the list of references appended to this paper, see p. 31.

ess, but it is a key variable. The inventor of this gaging method, J. O. Almen, has compared the role of Almen intensity in shotpeening to the role of furnace temperature in heat treating: it must be adjusted to give the desired results, and then repeated every time the same process is carried out on the same parts. By itself alone, the correct furnace temperature does not produce correct results: the time at temperature; the method of cooling; the furnace atmosphere; and, most importantly, the metal which is treated must be correct to produce the desired results. When the material or size of the parts change, the other variables must be adjusted.

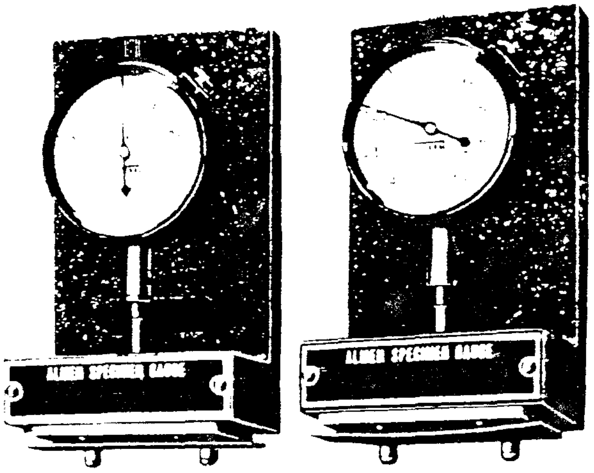


FIG. 1.—**Almen Gage** and Test Strip.
Note curvature of test strip under gage at right.

This paper is concerned with methods of adjusting the Almen intensity to compensate for changes in other variables.

ANALYSIS OF INTENSITY SPECIFICATION

The intensity specification is given in a form such as 0.012 to 0.016 A-2. Literally translated, this means that a flat steel strip, type A, which is 0.051 in. thick and of Rockwell hardness C 47, shall be firmly attached to a back-up fixture and exposed to the shot stream in exactly the same manner as the workpiece. When it is then removed from the fixture, it will be curved convex toward the peened side. This curvature is measured on the test gage type 2 (1, 2) and shall show an arc height, over a chord of 1.250 in. between 0.012 and 0.016 in.

The curvature measured on the gage is the result of a bending moment. With the standard dimensions of the test strip we can calculate the bending moment M as a function of the arc height h and chord length c from the formula:

$$M = 8EIh/c^2$$

which works out to

$$M = 1270\,h \text{ in-lb}$$

and for $h = 0.014$ in. this is a bending moment of

$$M = 17.8 \text{ in-lb}$$

From measurements of residual stresses it is known that this bending moment is produced by compressive stresses in a surface layer which is a few thousandths of an inch thick. To obtain a more graphic idea of the force acting in the strip we assume that it is concentrated on the surface; this will give a low estimate. The force on the surface of the strip then is

$$F = 2M/t = 700 \text{ lb}$$

on a width of 0.75 in.

Expressed as surface force per in. width, this will be

$$f = 700/0.75 = 935 \text{ lb per in. for } h = 0.014$$

or, in general, for the A strip

$$f = 66{,}600\,h \text{ lb per in.}$$

It is this compressive force, acting in all directions on the surface, which prevents cracks from opening.

Actually, there is, of course, no force "on the surface." Instead, a slightly larger force, somewhat below the surface, is the resultant of the residual compressive stresses. For instance, if the residual compressive stress were 150,000 psi, our surface force of 935 lb per in. would correspond to a depth of 0.006 in. to which the stress extends. Or we may assume, more realistically, that the stress tapers off towards the interior according to a parabola whose vertex is at the surface. With a stress at the surface of 150,000 psi we would then have an average stress of 100,000 psi and a depth of 0.009 in. at which the compressive stress is zero.

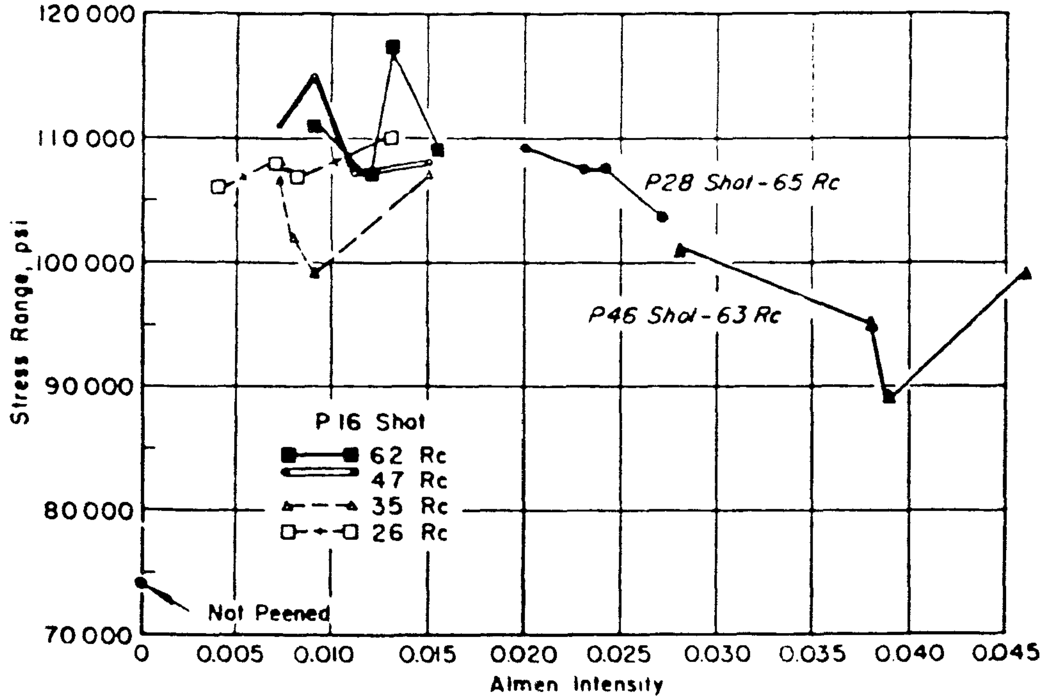


FIG. 2.—Effect of Peening Variables in Endurance Stress Range of Steel Coil Springs of 0.148 Diameter Wire.

COVERAGE, SHOT SIZE AND SHOT HARDNESS

A specified intensity can be obtained in several different manners. The intensity reading in a given situation depends on the time during which the strip is exposed to the shot stream. For the first few seconds the arc height increases in proportion to the time of exposure; it then reaches a limit beyond which it will not increase. A given intensity always implies that it is achieved at saturation. Some specifications ask for "complete visual coverage" to make sure of saturation. Visual coverage is generally an excellent index of saturation, but visual inspection is difficult or impossible in the case of hard workpieces or of soft shot.

It has been shown that high partial coverage can also produce excellent results, and in mass production industries the saving in time achieved by partial coverage justifies the expense of life tests to check the efficiency of the treatment. Where life tests for this purpose would be too expensive, the conservative procedure is to work with saturation and complete coverage.

One way to achieve equal Almen intensities by different treatments is to change size or hardness of the shot and to readjust the shot velocity to give equal intensity. For instance, instead of using large shot at low velocity, one can use smaller shot at higher velocity to obtain the same Almen intensity. In practice, it turns out that smaller shot is generally more economical to use, because for the same total volume it has more surface and produces coverage more quickly. Shot hardness makes no difference to the intensity as long as the shot is harder than the test strip. When the shot is softer, the intensity becomes less or the velocity must be increased. It is worthy of note that even shot as soft as Rockwell C 26 produces good intensity, as measured by arc height, on the test strips which have a Rockwell hardness of C 47.

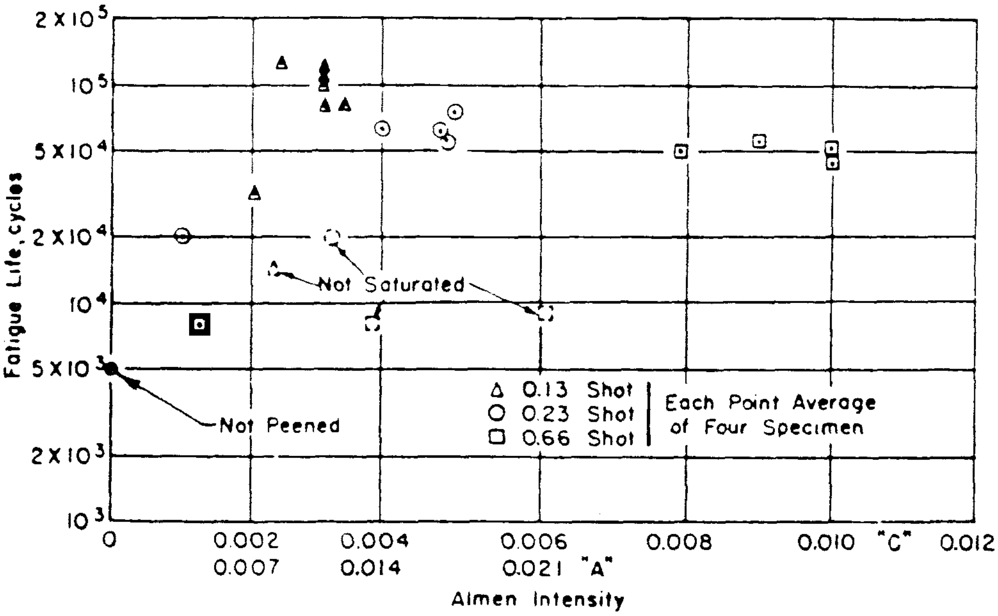


FIG. 3.—Effect of Peening Intensity on Fatigue Life of Leaf Springs.

CORRELATION OF PEENING INTENSITIES AND PEENING EFFECT

The remainder of this paper will concern itself with the question whether the same Almen intensity, produced by different methods, has the same effect on the workpiece. We shall see that in some cases it has and in others it has not and shall then find an index which can be used to specify peening results without prescribing all the details of the operation.

On Spring Steel:

The standard test strip is made of a spring steel; equal effects on the standard strip correspond very closely to equal effects on steel springs as shown by Figs. 2 and 3.

The chart of endurance stress range of springs, Fig. 2 (3), and the chart of fatigue life of leaf springs, Fig. 3 (4), both show that endurance is very significantly improved by shotpeening; that the improvement extends over a wide range of intensities; that the differences which might be assigned to different shot hardness or different shot size are less than the scatter apparent in the results. Figure 2 shows that coverage is necessary to develop the benefits of peening. In other words, to specify results for shot peened steel springs, it seems sufficient to specify a broad range of permissible intensity regardless of the shot size and shot hardness used to obtain the intensity.

This result is, of course, not surprising: steel springs were the oldest and most widespread application of shot peening. The standard Almen test strip was therefore wisely made of spring steel and equal intensities may be expected to correspond to equal results.

On Aluminum:

With aluminum alloys to which shot peening is now widely applied in the aircraft industry, the matter is quite different: in one case, a plant wanted to change from malleable iron shot to cast steel shot. In order to check the effect on production parts test strips of aluminum crankcase alloy, to the dimensions of the standard Almen C strip were made with results (5), as follow:

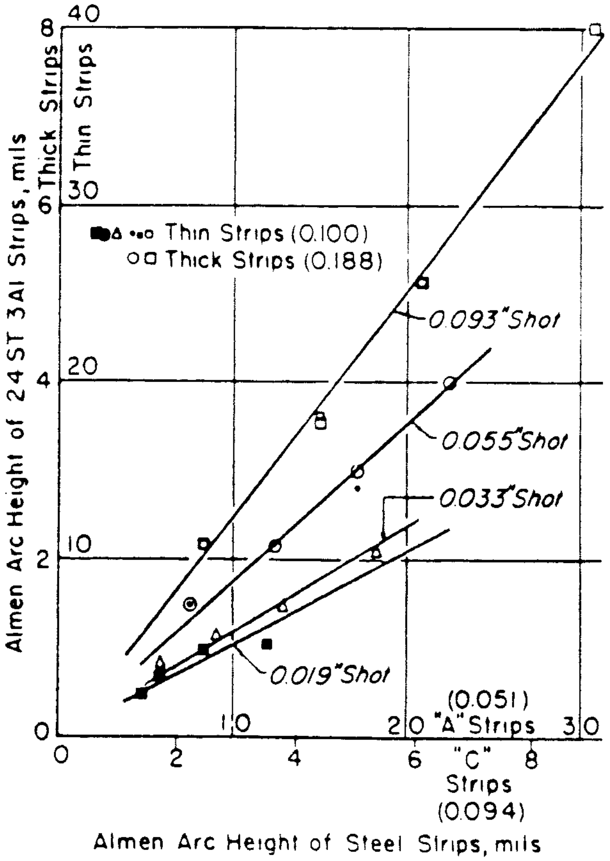


FIG. 4.—Effect of Peening on Curvature of Aluminum Strips.

Shot Type	Air Pressure, psi	Intensity	Curvature of Aluminum Strip, in.	Remarks
Cast Steel . . .	20	0.015 A-2	0.010	
Malleable Iron	40	0.015 A-2	0.030	Over-peened appearance

The malleable iron, being softer than the steel test strip, required more air pressure to produce the same intensity. On the aluminum alloy, which is much softer than either cast steel or malleable iron shot, the greater air pressure used with the malleable shot produced much more peening effect.

Aluminum and steel also respond quite differently to a change in shot size. For the same Almen intensity, larger shot has much more effect on aluminum than small shot. This difference is not nearly as easy to explain as the effects produced by different shot hardness. It is conjectured that aluminum is more inclined to yield to the large shot because it hits with a lower velocity, and that the sensitivity of aluminum to strain velocity at the values of interest here is quite different from the sensitivity of steel.

Figure 4 shows the relation between Almen intensity and curvatures produced on aluminum strips with different shot sizes. All combinations of four different shot sizes and four different air pressures were used to saturate steel test strips and aluminum test strips of two different thicknesses. For each shot size, the curvature of the aluminum strips was proportional to the Almen intensity, but the relation was different for each size of shot, with the larger shot more effective than the smaller. For the same Almen intensity, a stream of 0.093 in. shot produces over twice the curvature which a stream of 0.033 in. shot would produce.

The curvatures produced on steel strips of different thickness by any one treatment were inversely proportional to the squares of the thicknesses, as would be expected. The curvatures of thick and thin aluminum strips did not follow this relation, probably because the thinner strips, backed up by steel, could not be compressed elastically as much and therefore had to yield more.

EQUIVALENT ALMEN NUMBERS

The effect of different shot sizes on aluminum has been suspected for some time. Many companies therefore specify not only the Almen intensity but also the shot size. This practice is very satisfactory within any one plant, or for outside production of large quantities, for which special setups are well justified. For outside production of smaller lots, the specification of shot sizes may force the shop to change shot when changing from parts for one customer to parts for another customer. This takes time, produces delays, and is, of course, also expressed in higher costs.

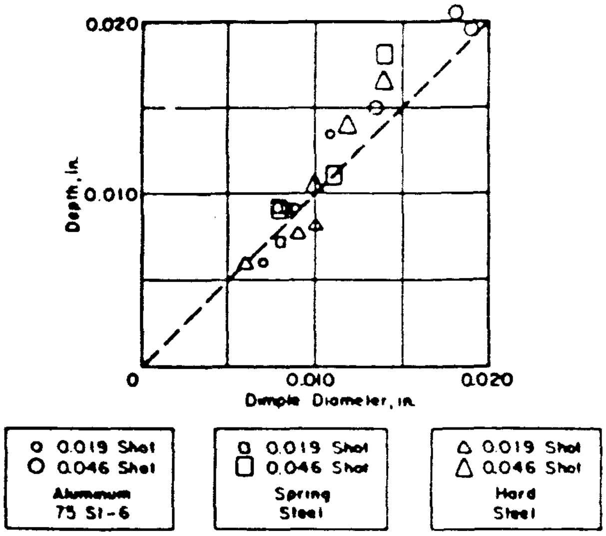


FIG. 5.—Depth of Compressed Layer *versus* Diameter of Peened Dimple.

Figure 4 shows that equal static effects of shot peening can be produced by different combinations of shot size and intensity. It is also known, as shown by Figs. 2 and 3, that fatigue life is not sensitive to minor variations in the peening treatment. Therefore, it appears that "equivalent" shot peening treatments can be specified.

We define equivalent shot peening treatments as those combinations of shot size, shot velocity, and angle of impingement which produce equal effects. It is obvious that the addition of the word "equivalent" in specifications such as "0.012 A-2 with 0.055-in. shot or equivalent", will permit the shop more latitude in the methods used to achieve the desired results and will thereby increase production and reduce cost. It is also obvious that the measure of equivalence must be clearly defined if consistent results are to be expected.

There are two measures of equivalence, each with its own advantages and difficulties. They are equivalence by arc height and equivalence by dimple diameters.

Equivalence by Arc Heights:

Arc height of the steel test strip is the accepted measure of peening intensity but does not necessarily correspond to equal peening results on materials other than steel of spring hardness. "Treatments equivalent by arc height" are those treatments which produce equal arc height on test strips made of material equal to that of the workpiece in composition and physical properties. Full coverage is, of course, always implied.

For instance, referring to Fig. 4, the following combinations of Almen intensities and shot sizes all produce the same curvature on strips of aluminum alloy 2024S T3.

0.008 A-2 with 0.093 steel shot
0.011 A-2 with 0.055 steel shot
0.017 A-2 with 0.033 steel shot

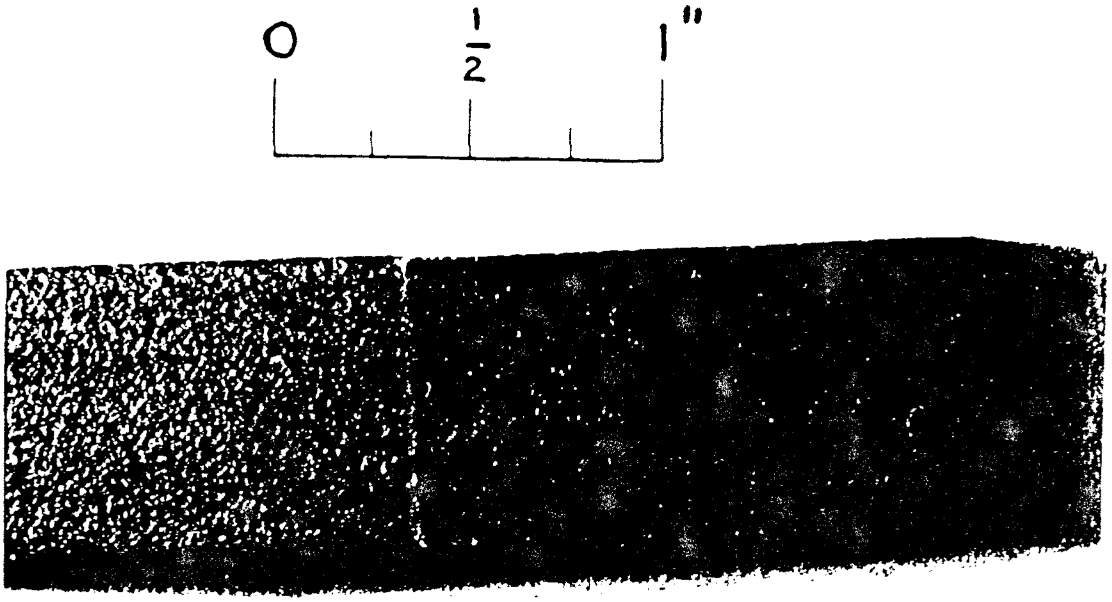
We would, therefore, consider these treatments as "equivalent by arc height for 2024S T3."

This type of specification would still refer to the standard Almen strip and to the shot size for process control but it would permit the shop to substitute an available shot size for a specified shot size if the Almen intensity is also adjusted to produce the equivalent results.

Equivalence by Dimple Diameter:

The usual visual inspection for coverage relies on the dimples or shot impressions to indicate that a point has been hit by shot. The same dimples, if they are inspected before coverage is achieved, can be used as a measure of the peening effect whenever the shot is harder than the peened material.

Almen has observed that the peak value of the residual stress produced by peening depends on the material and that the depth of the compressed layer is probably proportional to the diameter of the peening dimple (6).



Saturated at left. Unsaturated at right.

FIG. 6.—Enlarged View of Peening Dimples on Aluminum (0.021 A2 with 0.093 in. shot).

To confirm this observation, specimens of aluminum alloy 7075S T6, of spring steel and of steel of Rockwell hardness C 53 were peened with two different shot sizes and three different air pressures. The dimple diameters were measured, before full coverage, with a Brinell microscope. The residual stresses were determined by the etch method of Waisman and Phillips (8). When the depth to which the compressive stress extends is plotted against the dimple diameters, as in Fig. 5, it shows excellent correlation, regardless of shot size and of material. Figure 6 shows an enlarged view of peening dimples in aluminum.

The residual compressive stress is the result of plastic deformation and extends to approximately the same depth as the plastic deformation. To illustrate further the close relation between dimple diameter and depth of the deformed layer, some relatively large dimples were made in mild steel and treated by Valentine's method (7) to show the depth of plastic deformation. Figures 7 and 8 show the depth under a shallow and a deep impression made by using a $\frac{1}{4}$-in. steel ball. The grains enlarged by heating after dimpling indicate the extent of the plastically deformed region.

It may seem surprising that the depth of the deformed layer depends on the diameter of the dimple rather than on the depth of the dimple. This is a result

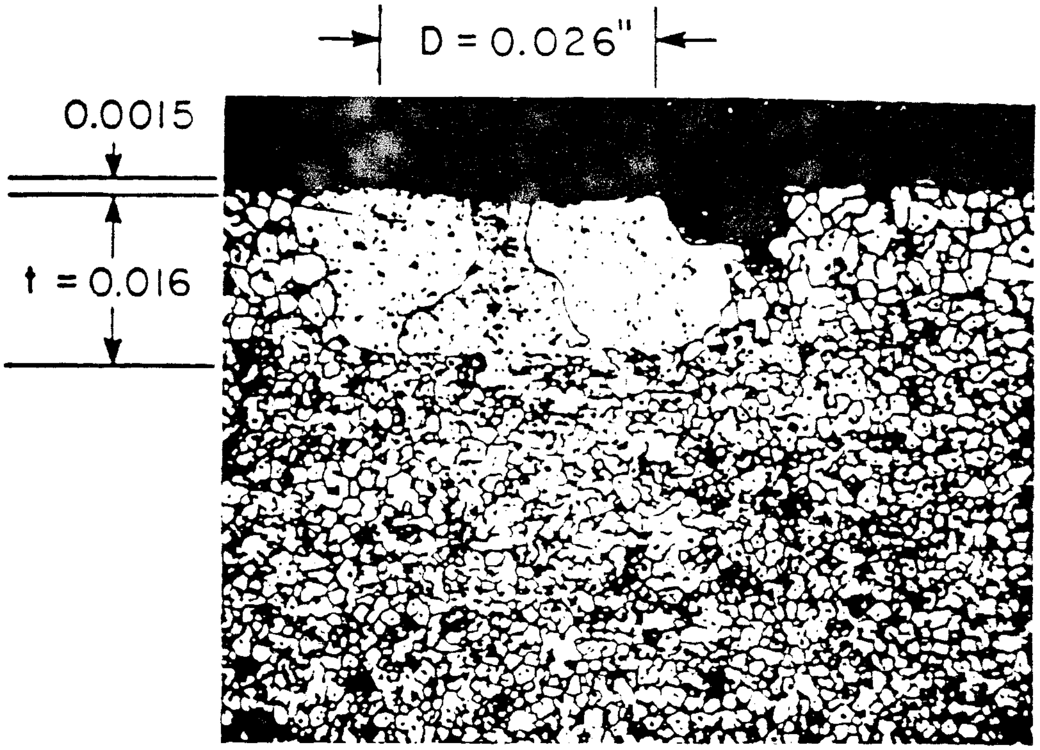


FIG. 7.—Photomicrograph of Grain Growth Under Shallow Indentation Made by ¼-in. Ball.

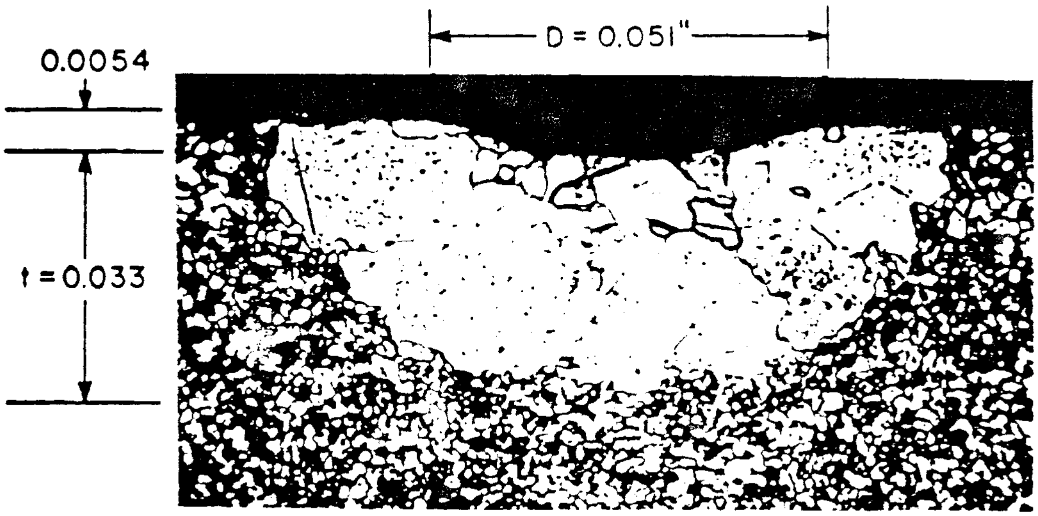


FIG. 8.—Photomicrograph of Grain Growth Under Deep Indentation Made by ¼-in. Ball.

of the yielding of the deformed material: as long as the deformation is elastic, the contact pressures are proportional to the depth of penetration, but the contact pressures become more equal after yielding sets in and approximate a pressure uniformly distributed over the contact area. With such a pressure distribution, the depth of plastic deformation becomes a function of the width of the loaded area.

A measurement of the diameter of the peening dimples thus becomes a measure of the depth of plastic deformation and of the depth to which the compressive residual stress extends. The dimple diameter is also a measure of the peening effect because the peak value of the residual stress produced by peening is a function of the material and sometimes of the amount of plastic deformation; therefore, the peak residual stress cannot be varied independently of the depth of the peened layer.

For these reasons it seems reasonable to take equal dimple diameters as an indication of equal peening effects.

because otherwise there are no dimples. It requires some judgment in measuring the dimples because they may be somewhat uneven in size.

The arc height method requires the preparation of special test strips. In the case of carburized gears, for instance, the test strips would also have to be carburized. Only a few of these strips are required to establish equivalence. Standard Almen strips are used for process control. The test strips can be kept for permanent record. The measurement of equal arc heights is subject to less error than the measurement of dimple diameters. It appears that the arc height method is superior in reliability but higher in cost.

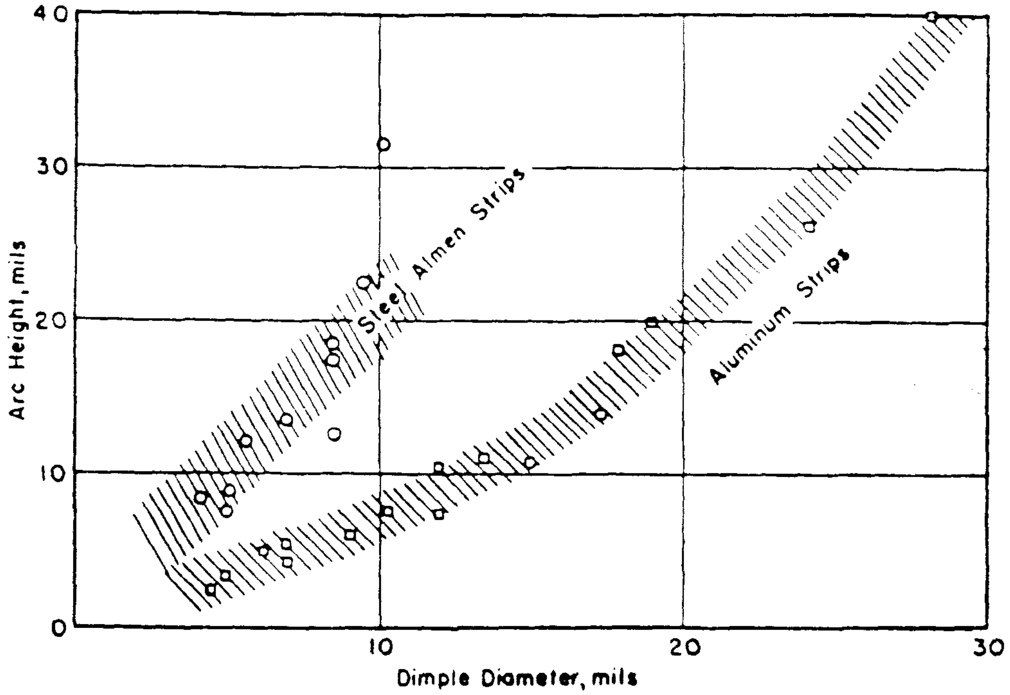


FIG. 9.—Relation of Dimple Diameters and Arc Heights Produced by Peening.

Comparison of Two Methods:

To establish the equivalence of two peening treatments, there are two proposed methods: one is by measurement of the arc height produced on strips made of the same material as the peened piece; the other by inspection of the peening dimples on the peened piece before saturation. The two methods correlate well with each other as shown in Fig. 9 where arc height of the strips and diameters of the dimples on the same strips are plotted against each other. Each of the methods has its advantages and shortcomings.

The dimple method is simple and inexpensive. It can be used only if the shot is considerably harder than the work

VALIDITY IN FATIGUE

The most frequent use of shot peening is to increase resistance against fatigue in service. Only service experience can tell conclusively whether two given treatments are truly equivalent. Such service experience can be obtained only when production quantities are fairly high and then only after enough time has passed to accumulate statistically significant data.

To assume that equal static effects, as measured by arc heights or by dimple diameters, correspond to equal fatigue effects seems quite safe in the case of shot peening because previous fatigue tests, as shown in Figs. 2 and 3 have shown that the results are not sensitive to moderate variations of shot size, shot material, or intensity. This requires, of course, that the shot be small enough to reach into the sharpest grooves.

To be on the conservative side, one could limit the range in which equivalence may be established to plus or minus two or three steps in the scale of standard shot sizes, and, of course, specify a maximum shot size in accord with the geometric requirements of the part. Even this limited freedom of action would often save valuable time in the shops which perform the peening.

CONCLUSION

The standard Almen test strip and gage is an excellent tool for control of the shot peening process. It measures the surface force produced by peening a steel strip.

Besides being a process control, the Almen intensity is also a good measure of the peening effect on medium hard steel, such as springs. It is known that the Almen intensity alone does not measure the peening effect on aluminum alloys and it is doubtful whether by itself alone it measures the effect on very hard steel and on soft materials. Therefore, it has become customary to specify shot size and shot material besides the intensity. Specification of results rather than of process details would be more desirable.

This paper shows two possible ways of measuring the peening effect and correlating it with an Almen intensity: it can be measured by the arc height of a special test strip or by the dimple diameter. Specification of the peening effect in terms such as, "equivalent to a given intensity with a given shot", would make specifications in terms of process details unnecessary.

The proposed method would, of course, not replace the use of Almen strips and Almen gage, but it would be a way to use these tools more effectively.

Acknowledgments:

It is a pleasure to acknowledge the help given to the author by his associates at Metal Improvement Co. The effect of shot size changes on aluminum was first observed on work done by this company for Lockheed Aircraft Corp. and investigated by K. Sparling of Lockheed. Measurements of residual stresses, shown in Fig. 5, were performed by Krause Western Labs. under the direction of J. Waisman. Micrographs were prepared by H. Pellett of Metal Control Labs.

REFERENCES

(1) "Soc. Automotive Engrs. Manual on Shot Peening," Soc. Automotive Engrs., New York, N. Y.

(2) "Soc. Automotive Engrs. Handbook", p. 205-211 (1956).

(3) F. P. Zimmerli, "Shot Quality," *Steel*, Oct. 18, 1948, pp. 126-129.

(4) R. L. Mattson and W. S. Coleman, "Effect of Shot Peening Variables and Residual Stresses on the Fatigue Life of Leaf Spring Specimens," *Transactions*, Soc. Automotive Engrs., Vol. 62, pp. 546-556 (1954).

(5) H. J. Noble, "Shot Peening Applications in the Aircraft Industry," paper presented to

Iron and Steel Technical Committee Soc. Automotive Engrs., Division XX, Oct., 1953.

(6) J. O. Almen, "Fatigue of Metals as Influenced by Design and Internal Stresses," Surface Stressing of Metals, Am. Soc. Metals, Cleveland, Ohio (1947).

(7) K. B. Valentine, "Recrystallization as a Measurement of Relative Shot Peening Intensities," *Transactions*, Am. Soc. Metals, Vol. 40, pp. 420–434 (1948).

(8) J. L. Waisman and A. Phillips, "Simplified Measurement of Residual Stresses," *Proceedings*, Soc. Experimental Stress Analysis, Vol. XI, No. 2.