SHOT PEENING

AND THE FATIGUE OF METALS

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FOREWORD

THE increased life imparted to stressed materials by shot peening has captured the interest of a rapidly growing number of engineers and technicians. This has been especially true with respect to vital war materials.

Through the research work of prominent engineers, great progress has been made in the interpretation and determination of the technical aspects of shot peening and in developing the technique for commercial operation. Special recognition for leadership in this field is accorded to J. O. Almen of the Research Laboratories of General Motors Corp.; and to the following men for their important contributory work: Dr. O. J. Horger of the Timken Roller Bearing Co.; F. B. Zimmerli of Barnes-Gibson-Raymond Div.; and H. F. Moore, for many years Professor of Engineering Materials at the University of Illinois.

Professor Moore is famous in the engineering profession for his research work on the fatigue of metals. We were fortunate to be able to secure his services in conducting studies on shot peening, which he has pursued through many months of research and testing. Based upon these studies, his paper "Shot Peening and the Fatigue of Metals" presents a sound interpretation and analysis of the subject.

Our sponsorship of this publication stems from our having engineered and installed various special equipments for this process* from the moment it was first used commercially in this country.

We feel that Professor Moore, through his paper, has made a valuable contribution to the art of shot peening, and we take this opportunity to congratulate him.

From time to time, as additional findings and data on shot peening are established from continued research, it shall be our purpose to sponsor further publications on this subject.

AMERICAN FOUNDRY EQUIPMENT CO.

*Trade Name: WHEELAPEENING

Shot Peening and the Fatigue of Metals

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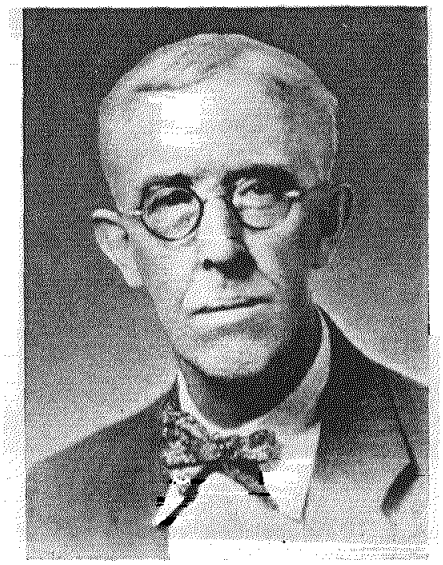


H. F. Moore

SHOT PEENING is a term used to denote the process of subjecting the surface of a metal machine part or structural member to a rain of metallic shot driven against the surface by the momentum of the shot as it is released from the rotating blades of a wheel, or by an air blast.[1] As the shot strikes the surface of the part, it produces a shallow layer of metal whose structure, which is made up of crystalline grains, is distorted, as shown in Fig. 1. This shallow layer of metal is made harder, stronger and less ductile than it was in the pre-peened state, and somewhat harder, stronger and less ductile than the metal farther below the surface, although the metal just below the shot-peened layer is somewhat affected by the shot peening.

Types of Structural Damage of Materials

Before taking up the discussion of how shot peening strengthens (or, if unskillfully done, may weaken) a metal under repeated stress five types of structural damage which may be done to structural and machine parts will be noted and briefly described.

(1) *Excessive Elastic Deformation.* As an example, a clutch plate spring may be made too light, so that even when the plate spring is flattened, the clutch will not transmit the required power. Shot peening would not be of service in such a case; it would change only slightly the elastic stiffness (modulus of elasticity) of the metal in the spring, and would not stiffen the spring so long as it was stressed within the elastic range of the original metal.

(2) *Elastic Buckling*, such as may occur in very long posts or columns. This is another case of failure, or at least the beginning of failure, which takes place within the elastic range of the metal. The buckling of a long, slender column (a long steel scale furnishes a very good illustration) when compressed length-wise will begin to buckle before the metal is stressed beyond its elastic range. Here, too, shot peening will be of very little aid. The critical load which will start elastic buckling will depend, not on strength, but on stiffness,—on the modulus of elasticity—

[1]The term "shot blasting" is sometimes used to denote this process. However the term "shot blasting" is more commonly used as denoting a surface *cleaning* process than as denoting a surface strengthening process. Hence the term "shot peening" is used in this publication.

Note: For Glossary of Technical Terms used in this paper, see page 23

Micrograph by Prof. R. E. Cramer

Micrograph of S. A. E. 1030 Shot-Peened Steel—Magnification 200 Times

Surface of S. A. E. 1030 Shot-Peened Steel
Magnification 100 Times

Surface of S. A. E. 1030 Steel, Carburized, Heat-treated and Shot-Peened
Magnification 100 Times

Surface of S. A. E. 1030 Steel, Carburized and Heat-treated but NOT Shot-Peened
Magnification 100 Times

Surface Outlines Traced from Micrographs

Fig. 1

Micrograph and Surface Outlines of Shot-Peened and of Unpeened S. A. E. 1030 Steel

of the metal, which will be very little changed by shot peening in the case of iron and steel, and not greatly changed for most other structural metals. Note again that we are talking about *elastic* buckling, not about buckling after the metal has passed beyond the range of elastic strength into the range where the deformation is partly plastic.

(3) *Plastic Deformation.* Deformation of a machine part which remains as "set" after load is removed is in itself structural damage in such parts as bolt and nut connections, which become loose when they are loaded beyond the elastic range of the metal.[2] In short and in medium-length columns plastic deformation reduces the stiffness of the metal very greatly, and buckling follows, leading to the collapse of the column. In statically loaded structural members failure by plastic bending under compressive stress (exceeding the yield strength in compression) is probably the most common type of structural damage due to stress. Shot peening increases the yield strength (resistance to plastic deformation) to a marked degree in the skin of the peened metal, and thus adds strength to resist plastic deformation in the outer layers of a structural part, just where the applied bending stresses are greatest, and help is most needed. However, this increase of yield strength may be partly or wholly lost if the peened metal is subjected to subsequent stresses up to or beyond the yield strength of the peened metal.

The effectiveness of shot peening in increasing the strength of medium-length columns (an airplane strut, for example) is worthy of further investigation.

(4) *Creep.* Creep is the continuing distortion of a material under a steady load. Damage by creep is similar in character to damage by plastic deformation, but creep continues, while simple plastic distortion does not increase after a few moments of load, or at any rate such increase is negligible. For the common structural metals creep is important only at elevated temperatures. Very little is known about the effect of shot peening on creep.

(5) *Fracture.* Fracture takes place under tensile or shearing stress. For example, in a compression test of cast iron, fracture commonly takes place under applied shearing stress along an inclined plane. While plastic deformation and creep are phenomena involving appreciable volumes of metal before appreciable structural damage is done, fracture may start at some point of localized stress concentration, such as a sharp shoulder on a shaft, and from that nucleus a crack may spread to fracture of the piece. In the case of a brittle metal, fracture may start at such a point under steady load; for ductile metals appreciable yielding takes place under a steady load, and this yielding "evens up" the stress distribution, cutting down the high peaks of stress, with localized plastic deformation rather than fracture. Frequently such localized plastic deformation produces no appreciable structural damage to the part as a whole.

However, under many cycles of repeated stress, especially cycles of reversed stress, a crack may start in the minute area of plastically deformed metal. This crack is due to the exhaustion of the ductility of the overstressed metal, and the crack, once started,

[2]The applied stress in the bolt is mainly direct tension with some concentrated stresses at the root of the threads. In general, shot peening is not of much aid in bolts, unless the threads are rounded at the roots, and shot fine enough to penetrate to the bottom of the threads is used. In special cases of bolts with reduced shanks shot peening has been used to counteract stress concentration at the surface of the fillets at the ends of the reduced portions of the shank.

will spread, even under a relatively low stress, causing final fracture without appreciable elongation or shortening of the piece fractured. This process of fracture of metals under repeated stress has been given the rather inappropriate name of "fatigue of metals."

Now such a spreading crack ("fatigue crack") usually starts under shearing stress within one or more of the crystalline grains which make up a piece of metal. However, as the crack spreads in a region of tensile stress, it soon takes up a direction at right angles to the principal tensile stress. In a region of compressive stress the crack frequently follows a direction of maximum shearing stress, and the crack progresses much more slowly than it does in a region of tensile stress. In structural metals increase of tensile strength is accompanied by increase of shearing strength, and so any process which increases tensile strength usually increases resistance to "fatigue," although not necessarily proportionately.

Shot peening increases the tensile strength of a metal just below the surface, and in addition, sets up a longitudinal compressive stress in the thin "skin" of shot-peened metal. It probably also sets up stresses in a transverse direction and in a direction perpendicular to the surface. Now a fatigue crack nearly always starts on the tension side of a beam,[3] and hence the longitudinal residual compressive stress must be overcome by applied stress before the stress on the tension side of the beam will be a *net* tensile stress. In effect the beam is strengthened materially against fatigue failure by this layer of metal under residual compressive stress *so long as* that stress is not removed by subsequent working stresses. Hence shot peening acts in two ways to increase the fatigue strength of the metal: (a) The tensile strength of the skin is increased[4] and (b) the effective tensile stress set up by a given load applied stress is diminished by the compressive stress set up in the skin by shot peening.

On the other hand, shot peening roughens the surface, and thus produces many shallow pits which cause localized regions of stress concentration, which tend to lower the resistance to fatigue. However, if care is taken to prevent jagged edges of peened metal[5] numerous fatigue tests show that the strengthening effect of shot peening properly done is, in general, greater than the weakening effect of the roughened surface, and that shot peening can be used to increase by a very considerable percentage the resistance of a metal to fracture under repeated stress.

Why Does Cold Working, and Especially Shot Peening Strengthen Metal?

Shot peening "cold works" the metal at or near the surface of a piece. Cold work is done on a metal when it is stretched, compressed or twisted beyond its elastic range,—beyond its yield strength.[6] Cold work increases the strength of a metal, but uses up part of its ductility, and if *too intense* cold work is done on a metal the ductility may be completely exhausted and a crack started. Then

[3] Except when the cross-section of the beam is of such a shape that the compressive stress is 50 per cent or more greater than the tensile stress, in which case fatigue fracture may start and slowly progress as a shear crack on the compression side of the beam. A T-beam with the flange in tension is an example of this.

[4] The increase of tensile strength due to shot peening presumably decreases as the hardness of the metal is increased.

[5] See page 11 for discussion of the weakening effect of jagged edges on shot peened parts.

[6] Some slight rise of temperature takes place under "cold" working, but the temperature reached is far below the "critical" temperature necessary to change the crystallization plan of the metal. Any change in crystal shape or orientation caused by cold working is a purely mechanical change.

the metal is not strengthened, but is weakened, especially under repeated stress.[7]

Cold work, in various degrees of intensity, may be done by stretching, compressing, twisting, cutting, grinding, drawing through a die, rolling lengthwise, rolling (of a circular rod) circumferentially, or by shot peening. Some of these processes affect a thin layer of metal near the surface which retains some residual stress after the cold working is finished,—sometimes tensile residual stress and sometimes compressive. At any cross-section of a cold-worked piece of metal the total force of the tensile stresses must balance the total force of the compressive stresses to produce equilibrium. Shot peening sets up compressive stresses near the surface of the metal, and these residual compressive stresses are balanced by residual tensile stresses in the interior of the metal. The rolling or drawing processes tend to produce a similar distribution of residual stresses, while simple stretching or compressing of metal tends to set up balancing groups of tensile and compressive stresses throughout the metal.

However, even in metal cold worked by stretching without producing any specially tough "skin," the fatigue strength may be increased. Tests made at the University of Illinois (1)[8] showed that a soft steel rod, stretched almost up to the ultimate tensile strength, had a considerably higher fatigue strength than did specimens cut from the rod before stretching it. This cold working by direct tension also increased the yield strength (resistance to plastic deformation) and, to a less degree, the tensile strength.

[7]Mr. J. O. Almen of the General Motors Research Laboratories reports that weakness due to too intense peening frequently can be traced to internal fractures resulting from the tensile stresses set up by too intense peening.

[8]Numbers in parentheses refer to the references given on page 24 of this booklet.

In these tests the cold-stretched metal was turned down at the critical section of the specimen so that any surface residual stresses were very largely removed.

Cold work, then, affects the fatigue strength of a metal in two ways: (a) it may set up a thin skin of metal which is under stress, in some cases compressive and in other cases tensile. If that stress is tensile it will be a weakening factor, if compressive it will be a strengthening factor. This residual stress is distributed across the cross-section of the piece in a regular pattern, and extends through the entire length subjected to the cold working. It is a large-scale or "macroscopic" effect. (b) Cold work, however produced, makes changes in the shape and orientation of crystalline grains of the metal, and, unless the cold work is so violent as to cause incipient cracks, the metal is strengthened and enough ductility remains to prevent cracking.[9] This second effect is a small-scale "microscopic" effect, and it is scattered throughout the cold-worked metal and possibly extends a short distance beyond the depth of cold working. It is a summation of many localized disturbances with resulting stresses within and between crystalline grains.

At the present time we have very little knowledge concerning the relative effectiveness of macroscopic and of microscopic cold working. Shot peening, producing as it does, a thin skin of surface metal under compressive stress, is beneficial either from the viewpoint of macroscopic or of microscopic cold working effects.

[9]The amount of ductility necessary to allow readjustment of stress distribution without cracking (dynamic ductility or crackless plasticity as it is sometimes called) is much less than the ductility measured by the stretch of a ductile metal in ordinary tension test. If in the metal of a structural or machine part *after assembly*, there remains as much as 3 or 4 percent ductility before fracture this amount would be quite sufficient for all probable readjustments of stress distribution which the part would be called on to withstand.

Permanence of Surface Compressive Stresses in Shot Peened Metal

How are the microscopic residual stresses set up in the skin of shot-peened metal affected by subsequent applied stresses, especially by thousands of cycles of repeated stress? Test data on this point are few, but tests at the University of Illinois (2) showed that even a single cycle of applied stress above the yield strength of the peened metal removed the greater part of the residual compressive stress. Repeated cycles of applied stress below the yield strength acted much more slowly, and no serious reduction of the residual compressive stress was found for applied stresses lower than about one third of the yield strength, even though a million cycles of stress were applied.

In the case of shot peened medium-carbon steel 25 cycles of reversed bending, with an applied stress which caused 0.02 per cent permanent set of the metal, removed 76 per cent of the residual stress in the skin of the shot-peened metal. Under reversed bending stresses of 62.5 per cent of the yield strength one million cycles of applied stress removed about 41 per cent of the residual stress. In the case of specimens of steel which had been carburized, heat-treated and then shot-peened the application of one million cycles of reversed bending with an applied stress of 40,000 p.s.i. did not appreciably reduce the residual compressive stress in the skin of the metal. Application of cycles of 50,000 p.s.i. stress (reversed bending) caused fatigue fracture, but a single cycle of applied reversed stress of 125,000 p.s.i. did not appreciably reduce the residual stress.

The question may be asked, "Why should there be *any* reduction of residual stress by cycles of stress lower than the yield strength, or at least by cycles of stress below the 'true' elastic limit?" The answer to this question seems to be that the yield strength is reached at such a stress that plastic deformation has become large enough to do structural damage to the material, and that the existence of any "true" elastic limit for any common structural material is very doubtful. Under any average stress, however low, there are probably localized plastic actions in many isolated crystalline grains of the metal, and under repeated stress there occur microscopic yieldings and a tendency to transfer some stress from locations which have yielded to those which have not, and thus there is a tendency towards a more nearly uniform stress distribution. However, the cumulative action of localized plastic yieldings seems to be almost, if not quite, negligible for stresses less than about one third the yield strength of the metal.

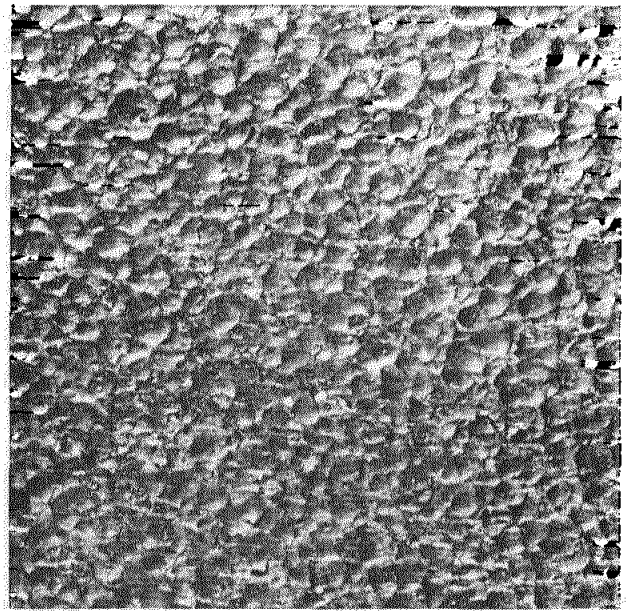
The Effect of the Rough Peened Surface on Fatigue Strength.

At first glance it seems that the rough surface of peened steel must set up localized stress concentrations which might well counteract any gain in fatigue strength due to increase of strength of metal, and to the thin skin of metal under residual compressive stress (See Fig. 1, page 6).

However, two factors tend to mitigate the damage due to this rough surface. The first of these factors is the lowering of stress concentration at any one notch or pit by the presence of other notches or pits near by. This has been shown by fatigue tests (3) and by photoelastic analysis of stresses at the base of multiple notches (4). Many notches, or pits, close together seem to share the stress concentration among them, while an isolated notch, or pit, has no such relief from the full stress concentration. Now, as is shown in Fig. 2, a shot-peened surface is covered with

closely spaced pits, and the mitigating factor of multiple pits is present.

Secondly, the maximum stress concentration is at the *bottom* of a pit or a notch, and the action of a rain of hard, spherical shot insures a smooth bottom to the pits,[10] which is a further mitigation of stress concentration. Data are not available to enable any quantitative estimate of the effective stress concentration on a shot-peened metal surface. However, the available fatigue test data show that in most cases the net effect of shot peening properly carried out on steel is to increase the fatigue strength in bending above that of polished[11] unpeened specimens.



Photograph by Prof. C. W. Dollins

Fig. 2

Surface of Shot-Peened Steel

S.A.E. 1030 steel, carburized and heat treated to a Rockwell "C" hardness of 62. Shot peened by the American Foundry Equipment Company with wheel type peening cabinet, New No. 19 shot used, and intensity of peening to an arc height ("h" in Fig. 6) of 0.010 inch on an Almen type "C" test strip.

Magnification of Photograph 7 Times

One caution is given as to stress concentration due to notches caused by shot peening. Figure 3 (A) shows thin fins of shot-peened steel pushed out at the corners of a sharp-cornered rectangular bar. These fins have jagged edges as shown in the side view (Fig. 3 (B)), edges so jagged and with notches so sharp at the bottom that, even with multiple notches along the edge, the stress concentration and the tensile stresses set up under the pushed-out fins may be severe enough to offset completely the advantages of in-

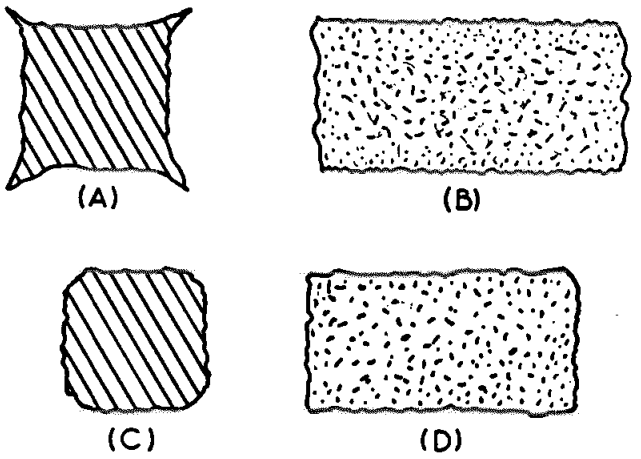


Fig. 3

Stress-Raising Fins on Shot-Peened Steel Bar

(A) Cross-section of Rectangular Bar with Sharp Edges; fins form under shot-peening.
(B) Side view of Rectangular bar with sharp edges.
(C) Cross-section of Rectangular Bar with Chamfered Edges; fins do not form.
(D) Side view of Rectangular bar with Chamfered Edges

[10] Mr. J. O. Almen of the General Motors Research Laboratory reports increasing the fatigue durability of steel by blasting with grit, which makes sharp-pointed pits in the surface of the metal. This suggests that the beneficial effects of peening or blasting may even overcome the damage due to sharp pits caused by grit blasting. However, he says, "Of course, round shot are much better."

[11] The term "polished" in this paper means the technique of polishing commonly used in preparing "polished" fatigue specimens. That technique consists of polishing the specimen with No. 00 emery cloth, or finer, so that the polishing marks are nearly parallel to the axis of the specimen. Polishing sets up surface stresses in the specimen. A few tests at the University of Illinois indicate that the polishing technique described above sets up a very small tensile stress in the surface of the specimen.

creased strength of metal and of the thin skin of surface metal under compressive stress. Figure 3, (C) and (D) shows how these sharp fins may be avoided by chamfering the edges of a rectangular bar or plate before peening it. Fatigue tests at the University of Illinois showed very clearly the damaging effect of sharp fins at the edges of a piece of metal.

How Is Fatigue Strength Measured?

The fatigue strength of a metal or of a metal part is evaluated from the results of a series of tests of specimens (or, better yet, of full-size parts) subjected to a series of applied stresses of known magnitude.[12] The variables in a series of fatigue tests are magnitude of applied stress and number of cycles of stress to cause fracture. A diagram plotted with magnitude of applied stress (S), or of load (P), as ordinates and number of cycles of stress (N) for fracture as abscissas, shows the results of such a series of fatigue tests. Such a diagram is called an S-N diagram, and it is convenient to plot the value of N (number of cycles of stress) to a logarithmic scale.[13] Figure 4 shows typical S-N diagrams for shot-peened steel and for the same steel not shot-peened. The steel was a rather soft steel, S.A.E. 1050, and the fact that there has been an improvement of fatigue strength in the shot-peened steel is evident at a glance. A quantitative estimate of the percentage of improvement in fatigue strength for the shot-peened steel may be made on either of two bases: (a) a comparison of the number of cycles of applied stress (length of "life") of the peened and the unpeened steel for the same applied stress, or (b) a comparison of the applied stress for a given length of "life." Table 1(A) shows the comparison on the basis of length of life for a given applied stress, and Table 1(B) shows the comparison on the basis of applied stress for a given "life."

[12] The commonest fatigue (repeated-stress) test is a test under complete reversals of bending stress. Tests for special purposes are sometimes made under repetitions of bending stress without complete reversal, under repeated or reversed torsion, and under direct axial stress (push-pull tests).

[13] S-N diagrams may be plotted either to ordinary (cartesian) coordinates, to log-log coordinates or to semi-log coordinates with applied stress as ordinates plotted to ordinary (cartesian) coordinates. The use of ordinary coordinates either makes the slope of the diagram in the upper ranges too steep for evaluation or stretches out the abscissas for large numbers of cycles of stress to inconvenient lengths. In this country the use of semi-log plotting has become quite general, though log-log plotting is sometimes used.

TABLE 1

COMPARISON OF "LIFE" AND STRENGTH OF S.A.E. 1050 STEEL, PEENED AND UNPEENED

The fatigue tests were made under cycles of completely reversed bending stress

(A) Comparison Based on Length of "Life" for a Given Stress

Applied Stress, p.s.i.	60 000	55 000	50 000	45 000	45 000
Cycles of stress for fracture, peened steel	85 000	200 000	600 000	more than 10 000 000	more than 10 000 000
Cycles of stress for fracture, unpeened steel	58 000	100 000	200 000	500 000	1 200 000
Increase in length of "Life" (number of cycles of stress for fracture) of peened steel over that of unpeened steel, per cent	46	100	200	Indefinitely large	Indefinitely large

(B) Comparison Based on Applied Stress for a given Length of "Life"

Cycles of Reversed Flexure for Fracture (Length of "Life")	50 000	100 000	500 000	1 000 000	5 000 000	10 000 000
Applied Stress for peened specimens, p.s.i.	63 500	59 000	51 000	48 500	47 000	47 000
Applied Stress for Unpeened specimens, p.s.i.	62 000	55 000	45 000	41 000	37 000	37 000
Increase of fatigue strength of peened steel over that of unpeened steel, per cent	2.3	6.9	13.0	18.8	27.0	27.0

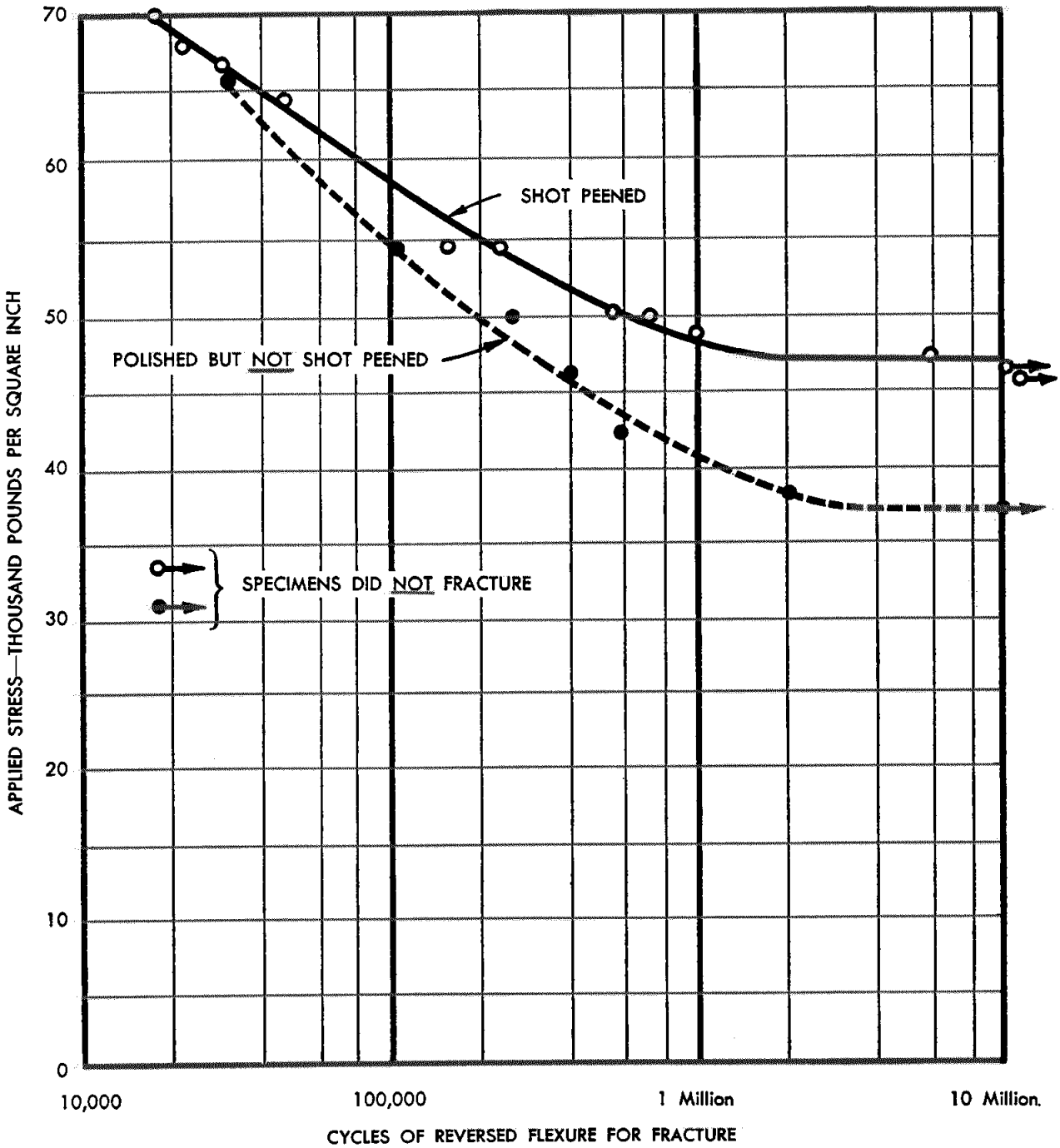


Fig. 4

S-N Diagrams for S.A.E. 1050 Steel, Peened and Unpeened.
Unpeened Specimens Were Given a Shop Polish

It will be noted that as the applied stress decreases the per cent gain in length of "life" for peened steel over that for unpeened steel increases, and that for 5,000,000 or more cycles of stress the S-N diagrams become very nearly horizontal so that quantitative comparison of length of "life" becomes impossible. Considering Table 1(B) it is seen that as the length of "life" increases the gain in per cent of applied stress for the shot-peened metal over the applied stress for the unpeened metal increases and, for this particular steel, becomes 27 per cent when the S-N diagrams have become practically horizontal.

The applied stress at which the S-N diagram for a metal becomes horizontal is called the endurance limit for indefinitely long "life," or, more commonly, simply the endurance limit. On account of the impossibility of comparing length of "life" of two metals for applied stresses below the endurance limit of either one of them, the comparison of stresses for a given "life" is to be preferred to the comparison of "life" for a given applied stress. There are, however, many cases in which length of endurance for satisfactory service is a more convenient basis for evaluating resistance to fatigue than is applied stress (or load, which is assumed to be proportional to applied stress). An examination of the S-N diagrams shown in Fig. 4 shows that a small percentage increase in applied stress (or load) means a much larger percentage decrease in length of service before fracture. Examination of many hundreds of S-N diagrams confirms this statement, and also shows that there is a considerable amount of "scatter" of results even in carefully conducted fatigue tests. This means that whether applied stress (or load) or length of "life" before probable fracture is used as the basis of computation by the designer of machine parts, a factor of safety (better called a factor of uncertainty) must be used.

If it is desired to design a machine part on the basis of a satisfactory length of service before fracture the designer should use for his computation a "life" many times (say from 10 to 20 times) the desired length of satisfactory service. On the other hand, if the applied stress (or load) for the desired length of satisfactory service is used, the reduction factor for that applied stress, based on the endurance limit for a satisfactory "life," after allowance has been made for stress raisers, residual stresses, size of part, range of applied stress during a cycle, size of piece and any other factors which may be judged to affect fatigue strength — this reduction factor then may be much smaller (say from 1.5 to 3).

Of course, exact knowledge of load, also of applied strength, of residual stresses, of stress raisers, of size effect, etc., is rarely, if ever, available. The designer must estimate the values for such factors, and must use a factor of safety (factor of uncertainty). This is true whether "life" for a given applied stress, or applied stress for a given life is chosen as the basis for design, and this factor must be numerically much larger when applied to "life" than when it is used as a reduction factor for the applied stress.

Results of Fatigue Tests of Peened Metals

Table 2 summarizes results of comparative fatigue strength of peened and unpeened specimens of various metals. The table is based on the applied stress for a "life" of 10,000,000 cycles of stress. For most steels this stress may be regarded as the endurance limit for indefinitely long life; for the phosphor bronze specimens the endurance

limit listed in Table 2 is probably somewhat higher than the endurance limit for indefinitely long life.

From Table 2 a comparison can be made of the tests in which the unpeened specimens were polished[14] with the tests in which the unpeened specimens were *not* polished. The percentage gain in strength due to peening is, naturally greater for those tests in which the unpeened specimens were not polished, but left with their "as received" surface finish. Examining the tests in which the unpeened specimens were polished it is seen that in eight of the ten items (items marked "YES" in the fifth column of Table 2) the fatigue strength of the peened specimens was greater than that of the unpeened polished specimens, the percentage of gain in fatigue strength ranging from 1 to 27 per cent. In two cases the fatigue strength of the polished, unpeened specimens was higher than that of the peened specimens, the percentages being 3 and 7 per cent respectively.

An examination of the detailed reports of these two tests brings out the fact that in the case of the S.A.E. 1045 steel, water quenched and drawn, it was recognized that the heat treatment might have set up residual stresses which acted to counteract the strengthening effect of the peening. In the case of the S.A.E. 9260 steel, oil quenched and drawn, while the fatigue strength at 10,000,000 cycles is very slightly less for the peened specimens than for the polished, for applied stresses above the endurance limit for 10,000,000 cycles, the strength of the

[14] See footnote on page 11 concerning the significance of "polished."

TABLE 2

EFFECT OF SHOT PEENING ON FATIGUE STRENGTH

Metal	Stress Cycle	Endurance Limit for 10 000 000 Cycles of Stress p.s.i. NOT Peened	Endurance Limit for 10 000 000 Cycles of Stress p.s.i. Peened	Unpeened Specimens, Polished	Gain in Fatigue Strength for Peened Specimen, per cent	Reported by
0.85% C. Steel Spring Wire	Torsion, 20 000 p.s.i. to maximum	95 000	135 000	NO	42	Zimmerli(5)
SAE 1095 Steel Music Wire	do.	90 000	135 000	NO	50	do.
18-8 Stainless Steel Wire	do.	65 000	110 000	NO	69	do.
13-2 Stainless Steel Wire	do.	80 000	120 000	NO	50	do.
Phosphor Bronze, SAE 81 Wire	do.	35 000	50 000(c)	NO	43	do.
18-8 Stainless Steel	Torsion, zero to max.	46 000	92 000	NO	100	Wahl(6)
NE 9470 Steel, carburized	Reversed Flexure	100 000	152 000	NO	52	H. F. Moore(7)
SAE 4032 Steel, carburized	do.	100 000	150 000	NO	50	do.
NE 9420 Steel, carburized	do.	100 000	153 000	NO	53	do.
SAE 1020 Steel Plate	do.	34 000	38 000	YES	12	do.
SAE 1050 Steel Plate	do.	37 000	47 000	YES	27	do.
SAE 1045 Steel, annealed	Reversed Flexure	39 500	43 800	YES	11	Lessells and Murray(8)
SAE 1045 Steel, water quench and draw	do.	80 700	75 000	YES	—7(a)	do.
SAE 9260 Steel, oil quench and draw	do.	108 600	106 000	YES	—3(b)	do.
Armco Iron	do.	26 800	27 000	YES	1	do.
SAE X4340 Steel, oil quench and draw	do.	66 000	78 000	YES	18	do.
SAE 1045 Steel, normalized and tempered	Reversed Flexure	31 000	32 000(d)	YES	3	Horger and Neifert(9)
	do.	31 000	34 000(e)	YES	10	do.
	do.	31 000	37 000(f)	YES	19	do.

(a) Residual stresses due to heat treatment may have offset benefits of shot peening. See author's closure in reference.
(b) Peened specimens showed much longer life under stresses above the endurance limit.
(c) For phosphor bronze there may be a reduction of endurance limit under more than 10 000 000 cycles. However, there is shown a distinct increase of strength due to peening.
(d) Peened with No. 28 shot. (e) Peened with No. 19 shot. (f) Peened with No. 22 shot.

peened specimens for a given number of cycles of stress was greater than that of the polished specimens. In other words the S-N diagram for the peened specimens crossed the S-N diagram for the polished specimens at about 10,000,000 cycles of stress. In this connection the results reported by Horger and Neifert (9) are of interest. Those results show that, for plain specimens with no sharp fillet, peening with No. 22 shot gave better results than peening with a smaller shot, No. 28, or with a larger shot, No. 19. It seems probable that whether peening a metal part increases fatigue strength more than does polishing depends on the proper choice of size of shot, velocity of striking, and time of exposure to the rain of shot, in other words on choice of the proper intensity of peening for a given machine or structural part. This matter of intensity of peening is discussed in a following paragraph.

While the available test data are too few for any final conclusion, in general, they indicate that, by using proper methods of shot peening, the fatigue strength of peened steel may be made somewhat greater than the fatigue strength of the same steel polished but not peened.

It will be noted that for the tests of specimens in which the comparison of fatigue strength was between that of unpeened and unpolished specimens and that of peened specimens, the fatigue strength of the peened specimens ranged from 42 per cent to 100 per cent higher than that of the specimens neither peened nor polished. The highest two reported values were 100 and 69 per cent respectively; both were for 18-8 stainless steel. For the remaining results marked "NO" in the fifth column in Table 2 the percentage of gain for the peened specimens showed no systematic variation from phosphor bronze to carburized and heat-treated alloy steel.

In heat treating steel a thin surface layer is not infrequently decarburized, and thus a weakening of the metal takes place at the surface, where the most damage can be done to resistance to bending and twisting strength. It seems probable that shot peening can be used to offset, at least partially, the weakening due to any such decarburization. (5)

In considering the use of shot peening as a means of strengthening metal parts of machines or structures consideration should be given to the possibility of polishing the surface of the part and of *keeping it polished* during service. Even if that can be done it seems possible to obtain somewhat higher fatigue strength by shot peening properly done, and in many cases shot peening is a more rapid and less expensive surface finish than is polishing.

The Effect of Shot Peening on Length of "Life" Under a Given Cycle of Stress

Comparisons of length of "life" under a given cycle of repeated stress cannot be made on a percentage basis alone since the percentage of gain of "life" due to peening increases rapidly as the magnitude of stress is decreased. Moreover, this percentage cannot be computed for stresses below the endurance limit of the unpeened metal. Values of percentage increase in "life" in actual service have been reported for springs and automobile parts, and the increase of "life" due to shot peening ranges from three times to twenty times.

It is equally true that comparisons of fatigue strength cannot be made on the basis of applied stress (or load) for only one length of "life," since many structural and

machine parts are designed to withstand only a limited number of cycles of stress. For a satisfactory comparison of the relative fatigue strengths of two metals, of peened and unpeened metals, or of machine parts made of different metals, an S-N or a Load-N diagram should be available up to several times the number of cycles to be expected in a satisfactory length of service for the part. This is true whether the comparison of fatigue-resisting value is made on the basis of an applied stress for a given "life" or on "life" for a given applied stress.

Shot Peening to Offset Stress Concentration at Fillets and Grooves

Shot peening has been successfully used at fillets and grooves to offset, by the added strength given to the metal, the stress concentration at the fillet or groove. Shot peening is especially effective in cases in which the shaft, or other part, is not polished, or cannot keep a polished surface. In shot peening grooves and notches (such as screw threads) it is obviously necessary to use shot smaller in diameter than the diameter of the rounded bottom of the groove or notch.

Relative Effectiveness of Shot Peening for Resistance to Bending, Twisting, and Direct Tensile or Compressive Stress

If a machine part is to be subjected to repeated cycles of direct axial tension and/or compression, shot peening is less effective in increasing its fatigue strength than is the case for a part subjected to repeated cycles of bending or of torsion. In a piece subjected to axial tension or compression, up to the yield strength of the core, the applied stress is uniformly distributed over the cross-section, and the bulk of the load must be carried by the unpeened core. At the yield strength of the core yielding takes place without much additional stress being taken by the core, although some of the stress is transferred from core to peened skin, which has a higher yield strength than the core. However, the area of cross-section of the core is very much greater than that of the cross-section of the peened skin, and the help which the core can get from the peened skin is not very great.

In a machine part under bending or torsion the stress varies from zero at the center of gravity of the cross-section[15] to a maximum at the surface. Then the peened skin of the piece resists a larger proportion of the bending moment than does an equal area of metal in the core, and adds a larger percentage to the strength of the piece than that added by the peened skin of the piece in direct axial tension or compression.

Under bending or torsion the peened metal adds strength just where it will do the most good.

Size Effect in Shot-Peened Parts

Figure 5(A) shows a shot-peened piece with thickness $2c$ and thickness of shot peened skin t. Figure 5(B) shows a piece with thickness $2c'$ with $c' = 2c$, and the same skin thickness t as in Fig. 5(A). Figure 5(C) shows a piece with thickness $2c'$ and skin thickness t' which is equal to $2t$. It seems probable that for pieces to resist flexure or torsion the increase of fatigue strength due to shot peening will be some function of the ratio of thickness of shot-peened skin to thickness of the piece. It cannot be stated at the present time that the piece shown in Fig. 5(C) will resist just as high repeated stresses as will the piece shown in Fig. 5(A), but there will be a tendency to equalize resistance to repeated flexural or torsional stresses if the thickness

[15] This is not necessarily true for a non-circular bar under torsion.

of the shot-peened skin is increased as the thickness of the piece is increased.

What Intensity of Shot Peening is Best?

Intensity of shot peening depends on the size of shot, material of shot, striking velocity of shot and length of exposure of the peened surface to the rain of shot.[16] At present no quantitative rules for assigning values to these factors so as to produce optimum results of peening can be given. It seems reasonable to assume that for deep penetration of peening larger shot should be used than for shallow penetration.

[16] Increase in length of exposure to the rain of shot increases the intensity of peening up to some value depending on the metal peened and the size, striking velocity and material of the shot; beyond that value, called the "saturation point" further length of exposure causes no marked change in intensity of peening. (See Fig. 7).

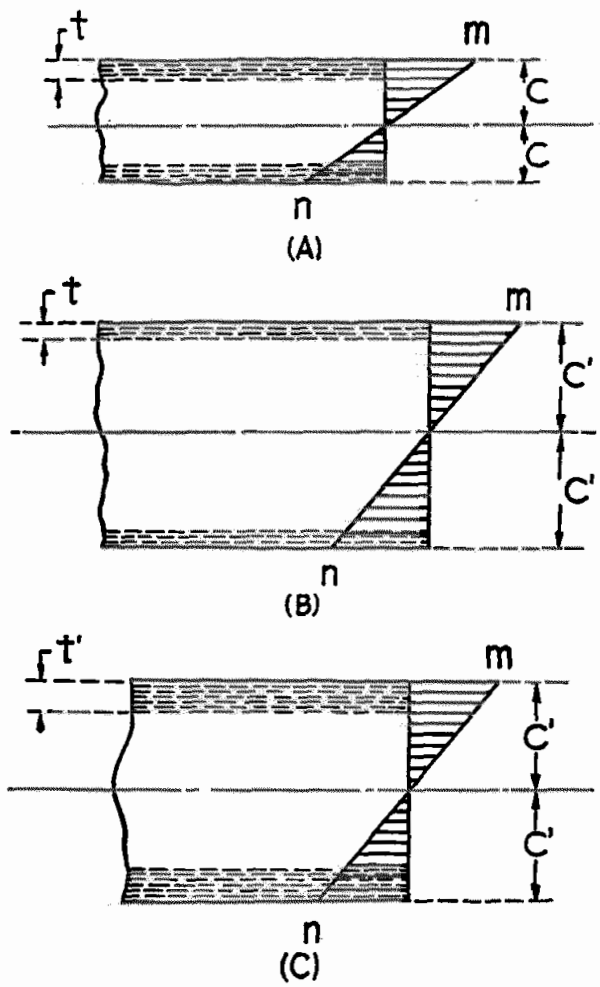


Fig. 5

"Size Effect" in Shot-Peened Metal

The effectiveness of the peened "skin" in increasing resistance to repeated stress will decrease as the (applied) "stress gradient" (slope of the stress line *mn* with the vertical) decreases, and will increase as the depth of peening *t* increases.

A useful device for measuring intensity and securing uniformity of peening is the Almen strip gage, shown in Fig. 6. (10) A thin flat strip[17] of rather hard steel S is clamped to a base B and peened for a given time with the same combination of size of shot, material of shot, and striking velocity of shot as is to be used in the peening of a structural or machine part. In fact the test strip is attached to a dummy of the same shape and material as the pieces to be peened. The intensity of peening, therefore, is representative of that given to the surface of the peened part. A time-intensity curve (See Fig. 7) for a batch of pieces may then be plotted from the results of tests made in this manner. After the exposure to the rain of shot for a given time the strip S is removed from the base B and is found to be curved, with the convex surface on the peened side. This is due to the stresses set up by the peening of one side. The curvature of the peened test strip is taken as a measure of the intensity of the stresses set up by the peening and hence as a measure of the intensity of peening. The distance h in Fig. 6, called the "arc height" is then a measure of intensity of peening. The choice of desired intensity of peening for optimum results is, at present, a matter for experience and judgment on the part of the operator of the peening process. The curvature of the Almen strip gage under

[17] Two test strips are in use for intensity determinations. For low intensities the "Almen A" strip is used; this strip is $\frac{3}{4}$ inch wide, 3 inches long and 0.051 inch thick ($\pm$0.001 inch). For high intensities the "Almen C" strip is used. This strip is $\frac{3}{4}$ inch wide, 3 inches long and 0.0938 inch thick ($\pm$0.001 inch). Both strips are made of steel with a Rockwell "C" hardness of 44-50.

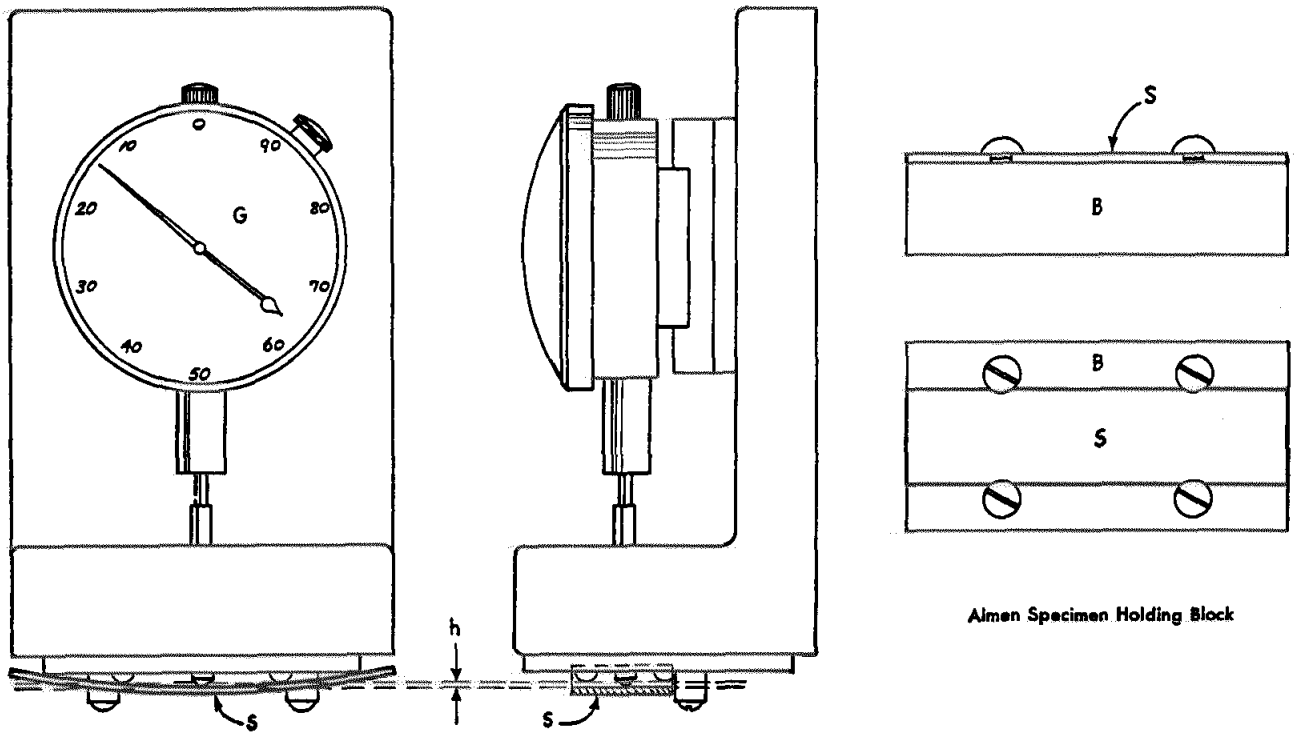


Fig. 6
Almen Test Equipment for Intensity of Peening

a given peening technique depends on (a) degree of coverage of the surface[18] (saturation) and (b) the depth of the stressed layer. There is probably some change in hardness as the depth is increased, but this is probably very slight.

Figure 7 shows two diagrams drawn with values of peening intensity as ordinates and time of exposure to shot (or quantity of shot) as abscissas. The desired intensity of peening, determined by the experience and judgment of the operator, is shown as OP. The curve marked A was obtained by using a given size of shot, material of shot and striking velocity of shot for various intervals of time, while the curve marked B was obtained by varying one or more of the above factors and making peening intensity determinations for various intervals of time. The time of exposure for securing the desired intensity of peening is quite critical for the peening technique corresponding to curve A, and for this technique for this particular metal a relatively large variation in peening intensity can be expected. Time of exposure is less critical for the peening technique corresponding to curve B, and for this reason for this particular metal the latter technique is to be preferred. In curve B it is seen that

[18] Considering the matter of coverage in some detail, the term may be defined as a uniform distribution of peening over the surface by such a quantity of shot that "saturation" is obtained. Saturation is reached when the part peened has been exposed to the rain of shot for so long a time (or to such a quantity of shot) that additional peening will not greatly increase the peening intensity as determined by the Almen strip gage. See Fig. 7 in which the point Y, curve B, is nearly at the saturation intensity.

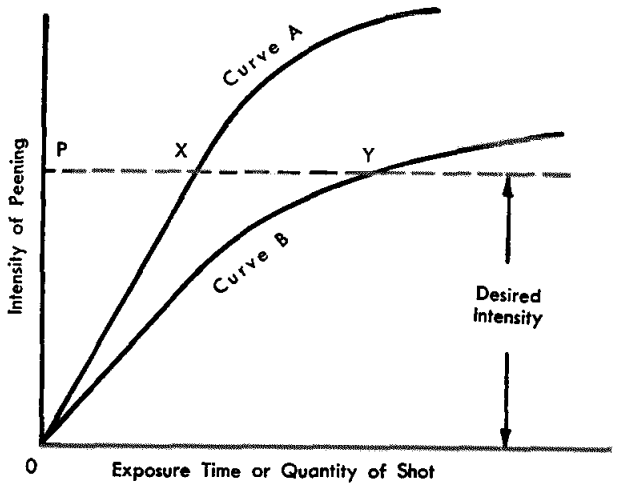


Fig. 7
Intensity-Time Curves

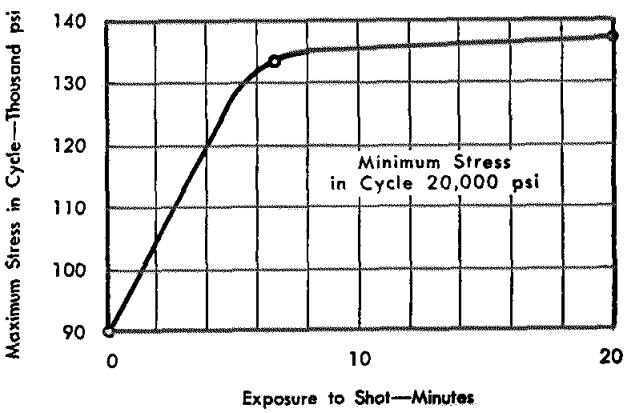


Fig. 8
Effect of Exposure to Shot on Fatigue Strength (Zimmerli)

the desired peening intensity was reached close to the saturation point.

Figure 8, from data reported by Zimmerli (5), shows the effect of time of exposure on fatigue strength, determined on the basis of applied stress for a "life" of several million cycles of stress. This diagram has a shape similar to that of the intensity-time diagrams shown in Fig. 7.

Figure 9 from Horger and Neifert's test results (9) shows the effect of peening intensity on fatigue strength. For the plain specimens tested (specimens without fillets) the maximum fatigue strength was obtained with a peening intensity indicated by an arc height of 0.0065 inch on an Almen "C" strip. However, for specimens with fillets the fatigue strength increased up to an intensity of 0.0100 on an Almen "C" strip.

It seems that peening beyond a certain intensity weakens the resistance of a part to repeated stress. Probably this effect of "overpeening" is due to cracks started in the peened surface of the metal, or just below the peened skin. At the present time experience, developed judgment and records of performance in service of parts similar to those to be peened constitute the best basis for determining the optimum intensity of peening for any given batch of parts.

Resistance to Corrosion-Fatigue of Shot Peened Metal

Shot peening does not directly affect the chemical attack of moisture on steel. However, the surface of shot-peened metal is under residual compressive stress, and before corrosion pits can form and start a fatigue failure, this peened and compressed skin resists cracking and delays, if it does not inhibit, the formation of the corrosion pits, which are the cause or the nuclei for possible spreading cracks. In this matter of corrosion as in the case of optimum intensity of peening, much more research work needs to be done. However, experience has shown that shot-peened steel is distinctly more resistant to destructive corrosion than unpeened steel of the same chemical composition.

Limitations of Shot Peening

Shot peening is not very effective in increasing the resistance to repeated stress of

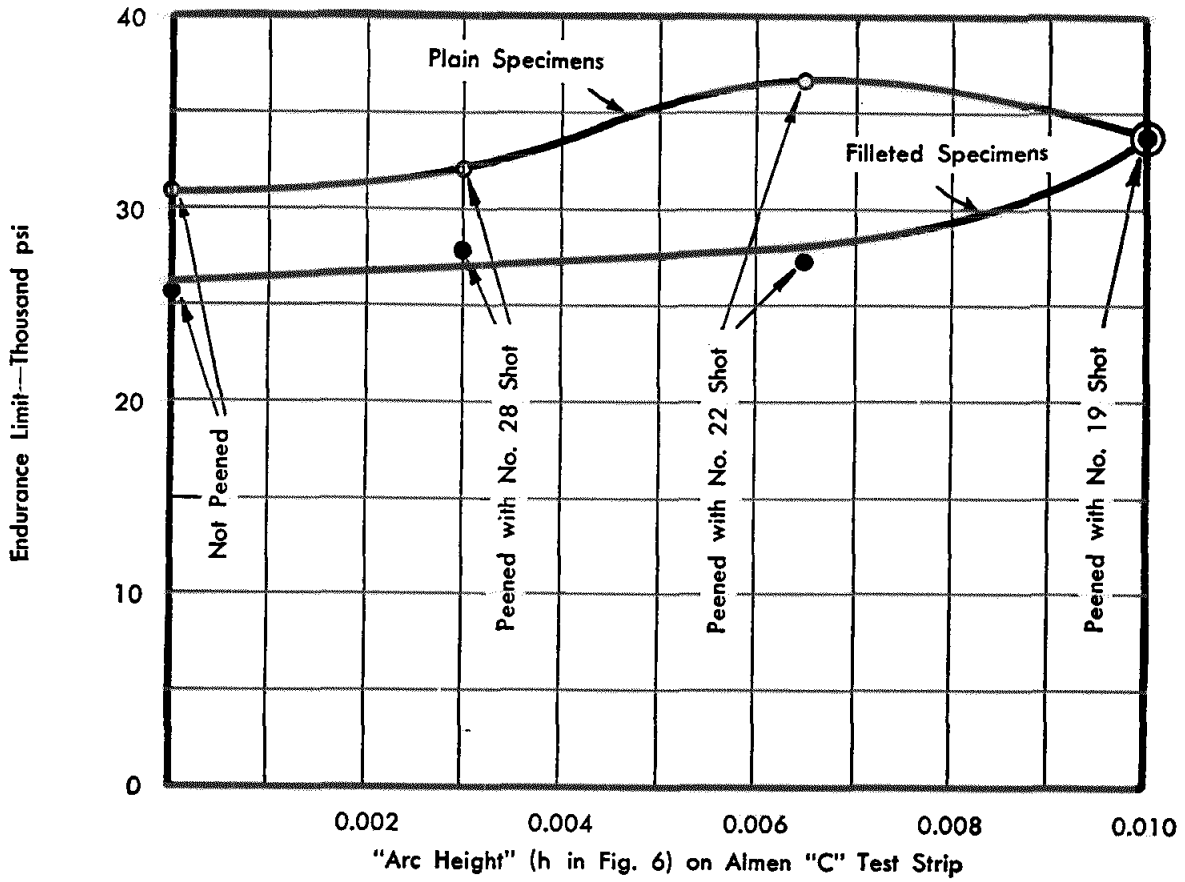


Fig. 9
Effect of Intensity of Peening on Fatigue Strength
(From test data reported by Horger and Neifert)

parts subjected to cycles of direct tension-compression load. Metal may be weakened by too high an intensity of shot peening. Much has yet to be learned about the details of the peening process before any very definite rules can be laid down for securing optimum results for a given machine part. The thickness of the shot-peened "skin" on a machine or structural part is probably not over 0.01 inch for small pieces, although it may be somewhat larger for large pieces peened with large shot with a high striking velocity. This means that shot peening cannot be expected to be so effective in increasing the fatigue strength of thick pieces as it has been found to be in the case of thin pieces. If there are cracks or seams in the base metal peening may not be effective.

Advantages of Shot Peening.

Shot peening can be applied to irregular shapes, in which heat-treating processes might cause excessive distortion, and in which rolling or drawing processes are not feasible. Shot peening can be applied to finished parts, such as springs, or to specific areas on structural and machine parts, as when shot peening is applied to the fillet of a shaft to offset stress concentration, or to the body of a shaft to resist pitting corrosion. It can be applied to parts such as gear teeth without causing appreciable distortion, while it produces a surface with improved

resistance to pitting corrosion under localized heavy stress at bearing points, and also with improved resistance to wear. Often shot peening can be used as a surface finish in place of polishing, with actual gain in fatigue strength. Such a substitution of shot peening for polishing often reduces production costs materially.

While shot peening needs much more research and study before its limitations and advantages can be finally evaluated, it has already proved its worth in strengthening many machine parts, some large and some small, some made of iron or steel and some of non-ferrous metal, some of hard metal and some of soft metal. In some cases it has replaced polishing, not only because it proved cheaper, but because it proved superior in strength. It is being used with apparent success to increase resistance to surface damage, such as light bruises, "fretting corrosion," pitting corrosion and decarburization. It seems certain that the field of usefulness of shot peening will be much enlarged in the near future.

Acknowledgements

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GLOSSARY OF TECHNICAL TERMS

Some of the technical terms defined in this glossary have not been standardized as yet, and some writers would use other terms. These definitions are given merely to state the meaning of the terms as used in this publication.

Stress—The intensity of the internal distributed forces which resist a change in the form of a body. Stress is measured in pounds per square inch.

Tensile Stress—The stress set up tending to lengthen and to pull apart the material under load.

Compressive Stress—The stress set up tending to shorten and to push together the material under load.

Shearing Stress—The stress set up tending to cause adjacent parts of the material to slide over each other. Example: the stress set up in the rivets of a riveted joint under tension.

Axial Stress—Stress in the direction of the axis of a body. Example: The tensile stress in a tie rod or the compressive stress in a short post or column.

Flexural Stress—The stress system set up in a body under bending. In a body, originally straight, and then bent there are set up compressive stresses on the concave side and tensile stresses on the convex side.

Torsional Stress—Stress set up in a body under twisting. In a round body under twisting the shearing stress varies from zero at the axis of the body to a maximum at the surface.

Residual Stress—Stress remaining in a body after fabricating or release of severe stressing. Examples: Stresses set up in quenched steel, in rolled or drawn metal, stresses near the surface of shot-peened metal.

Applied Stress—Stress set up in a body by the applied load. This stress is the stress computed by the common formulas of mechanics of materials.

Strain—The change per unit of length in a linear dimension of a body, which change accompanies change in stress. Strain is measured in inches per inch, or in per cent.

Strength—The limiting stress which a body can withstand without structural damage which impairs the proper functioning of that body as a structural or machine part.

There are various "strengths" for denoting resistance to different kinds of structura ldamage. Some of these are:

Yield Strength—The limiting stress at which, after release of load, a material exhibits a specified permanent strain (set). The amount of set specified is that amount which, for a given metal and a given use, is judged to constitute structural damage. Yield strength may be tensile, compressive or shearing. The value of 0.2 per cent (0.002 inches per inch) has been assigned as this specified set for a number of structural metals.

Tensile Strength—Under direct tension the maximum stress developed as the test specimen or the part is pulled in two. The maximum stress is based on the original minimum cross-section of the piece. The load (measured in pounds) accompanying this stress, is sometimes called the *ultimate load.*

Compressive Strength—In a body under compressive load fracture does not result from the compressive *stress*, but if fracture occurs at all, it is usually an accompaniment of shearing stress in a diagonal direction. However, the computed compressive stress at fracture is sometimes spoken of as the compressive strength.

Endurance Limit (Fatigue Strength)—The limiting magnitude and range of repeated stress which a material can withstand for a given number of times without fracture. If no number of repetitions (cycles) of stress is specified endurance for an indefinitely large number of cycles is understood. For most steels if 10 000 000 cycles of stress are withstood without fracture, indefinitely long "life" is assumed. The commonest cycle of stress used for evaluating the fatigue strength of a metal is a cycle involving complete reversal of stress.

Elastic Deformation—Deformation of material subjected to stress and strain not sufficiently great to cause permanent change of form (set). In most cases this is practically equivalent to stress and strain below the yield strength of the material.

Plastic Deformation—Permanent change of form after a short-time test (ordinary testing machine test). Practically this means deformation beyond the yield strength. Plastic deformation does not include the slow creep under long-continued steady load discussed in the next item.

Creep—The continued deformation of a material under long-continued steady load. For most structural metals creep is not appreciable except at elevated temperatures. (Tin, lead and zinc exhibit measurable creep at ordinary room temperatures.)

Elastic Stiffness (Modulus of Elasticity)—The ratio of stress to strain below the stress sufficient to cause appreciable plastic deformation.

Cold Work—If a ductile metal is stressed beyond its yield strength at room temperature it is said to be cold worked. In general cold work increases the strength of iron and steel, especially the yield strength. It decreases ductility, and somewhat increases the danger of cracking. Cold work usually

sets up residual stresses in the metal, which may increase or diminish the strengthening effect according as the stresses are compressive or tensile. Cold working may be done by stretching, compressing, bending, twisting, cold rolling, cold drawing, or by shot peening.

Carburized Steel—Steel which has been heated in contact with carbon or with certain carbon compounds. This treatment causes a "case" or "skin" of high-carbon content, and this skin if properly heat treated may be made stronger, harder and less ductile than the metal in the central "core" of the piece.

Nitrided Steel—Steel which has been given a hard, strong "skin" by being heated in contact with nitrogen or nitrogen compounds.

Macroscopic and Microscopic—These are terms used to denote large-scale (*macroscopic*) and small-scale (*microscopic*) phenomena. Example, The stresses computed by the ordinary formulas of mechanics of materials are *macroscopic*, involving an appreciable volume of material. The stresses within a crystalline grain of metal are *microscopic*, and may be quite different in direction and amount from the computed *macroscopic* stresses.

Photoelasticity—The distribution of stress in a body of given shape may be studied by making a model of a section of the body out of a transparent plastic material, and examining and counting the "fringes" which appear when the model is loaded and viewed by polarized light.

Ordinates and Abscissas—In a diagram drawn on paper any vertical distance from the horizontal base line is called an ordinate, and any horizontal distance from the vertical base line is called an abscissa.

Logarithmic Scale—A scale on which distances from the base mark are proportional to the logarithm of the number indicated on the scale. Example, the scales on a slide rule.

Optimum—The best, or the most favorable.

Shot—The shot used in peening is made of chilled iron, is spherical in shape, and is made by allowing a stream of molten iron to fall from a height into water, after which the shot are screened to standard sizes.

Peening—Striking the surface of metal with a very large number of light blows. The word is derived from the peen-hammer, which has a hemispherical end, and which has been used for centuries by blacksmiths and armorers to surface-work swords and other metallic products.

Almen Gage—A device for measuring the intensity of shot peening. It is the invention of Mr. J. O. Almen of the General Motors Research Laboratories.

S.A.E. 1030, etc.—A method of identifying the analysis of steel by means of a system of numbers. Set up by the Society of Automotive Engineers. For details of the system see the current Metals Hand Book, published by the American Society for Metals, Cleveland, Ohio.

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