SAE MANUAL ON

SHOT PEENING

DIVISION XX - SHOT PEENING

of the SAE Iron & Steel Technical Committee

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INTRODUCTION

This manual on Shot Peening is intended to be a practical aid to engineers, designers, and men in the shop, pointing out both some of the possibilities and some of the limitations of the process. It has been prepared by a group of men of broad experience with the process and whose leadership in the field is acknowledged.

Shot peening may be defined as the process of cold working the surface of a structural or machine part, by means of a driven stream of hard shot. The purpose of the process is to improve the fatigue properties of the shot-peened part.

While all factors which affect the improvement are not completely understood, it is generally attributed to the introduction of compressive stresses in the surface layer and to the slight hardening effect caused by the peening action of the shot. It is said that most fatigue failures occur only in tension, so the compressive stress in the shot-peened object is in effect a pre-loading device, opposite in direction to the stress applied in service. Thus, the actual service stresses are reduced to a safe level by the counter-effect of the pre-loading induced by shot peening.

The principle of improving strength of metals by cold working undoubtedly was discovered early in civilization, as ancient man hammered out his tools and weapons. In more recent times, the blacksmith hammered the tension side of buggy springs because he knew it made them better. However, it was not until 1927 that the glimmerings in the mind of man regarding this process were voiced by Herbert in his paper, "Work Hardening of Steel by Abrasion". (7). At a later date, definite claims were made in another paper, "Cloudburst Process for Hardness Testing and Hardening".

None of this information was very definite, but it was sufficient to arouse interest and to start additional investigations, largely in the spring industry. These investigations and their results were summed up in a paper given at the American Society for Metals 1940 Symposium on Surface Treatment of Metals entitled, "Shot Blasting and Its Effect on Fatigue Life". (38). This encouraged the publication of many articles from numerous laboratories and these added much to the pool of knowledge.

Shot peening is not the only method by which these beneficial surface stresses may be introduced into a part. The most important of the other methods are as follows:

Cold working by rolling, by stretching, by compressing, by bending and by twisting.

Heat treating, and in particular, surface treatments by induction and flame treating.

Changing the chemical composition of the surface layer by carburizing, nitriding, etc.

(7) (38) Numbers refer to Bibliography, Pages 42 and 44.

Shot peening possesses several advantages over any of these methods, such as flexibility, control of stress intensity, safety from the point of view of not introducing unwanted or harmful stresses by accident and, in many instances, economy.

II. DESCRIPTION OF PROCESS

The shot peening process is carried out usually in a cabinet in order to confine the shot and facilitate its collection for re-use, as well as to suppress dust.

The work to be peened is introduced into the shot stream usually by a mechanical means, which is so contrived as to expose the critical areas to the shot according to a predetermined program.

The shot consists of hard particles which are classified as to size, and the usual sizes range from 1/64 to 3/32 inches in diameter. Various kinds and types of shot are available (see IV. Shot, Page 6). Shot may be propelled by air or by a wheel, with velocities of the order of 200 feet per second.

The area covered by the shot stream is called the "shot pattern".* In the case of the pneumatic type of machine, shot is delivered from a nozzle and the shot pattern covers a circular area about two or three inches in diameter, depending on nozzle size and the distance to the work. The shot pattern from a wheel is fan-shaped, with an included angle of about 40° and a width somewhat greater than the width of the wheel itself. The length and width of the pattern depends on the distance of the work from the wheel.

Shot peening causes plastic flow in the surface of the object, stressing the material beyond its yield strength, which results in a residual compressive stress. The depth to which this compressive stress extends is dependent upon the properties of the material, the characteristics of the blast and the amount of shot striking the area being peened. The properties of the blast are defined by the velocity of the shot and its size and type. The amount of shot striking the area being peened is a function of the quantity of shot flowing, the shot pattern, manipulation of the work and the time of exposure to the blast. Measurement of these factors is described in VI. - PRODUCTION PROCEDURE, page 8.

III. SHOT PEENING MACHINES

Shot peening machines may be classified into two major categories, depending on the medium which propels the shot.

1. Air blast machines

2. Centrifugal blast machines

A typical peening machine is made up of the following major parts:

<u>Shot Propelling Device:</u> For accelerating the shot to the desired velocity.

<u>Elevator:</u> For returning the shot to the separator after passing through the projecting device.

*sometimes called "blast" or "spray" pattern

Separator: For removing broken or undersized shot.

Shot Adding Device: For replacing broken and undersized shot with new shot.

Work Conveyor: For handling the work so as to subject it to a definite controlled cycle under the blast.

Cabinet: For confining the shot within the machine.

Dust Collector: For removing the dust resulting from the blast.

1. Air Blast Machines

These machines may be subdivided into three kinds, depending on the method of introducing the shot into the air stream.

a. Suction-induction machines (Fig. 1)

In this type of machine, compressed air is allowed to expand through a nozzle which is provided with a port or auxiliary tube through which the shot enters the nozzle, as shown in Figure 2. The shot is drawn into the air stream by entrainment and is then accelerated by the air which is traveling at relatively high velocity.

This is the simplest machine and is used to peen small parts or small quantities, or when the required intensity of peening is low. It is used for laboratory work and for other applications when the shot size is changed frequently.

b. Gravity-induction machines (Fig. 3)

In this type of machine, the nozzle is identical to that of the suction-induction type, but the shot is introduced to the nozzle by means of gravity. This results in better control of velocity and flow rate.

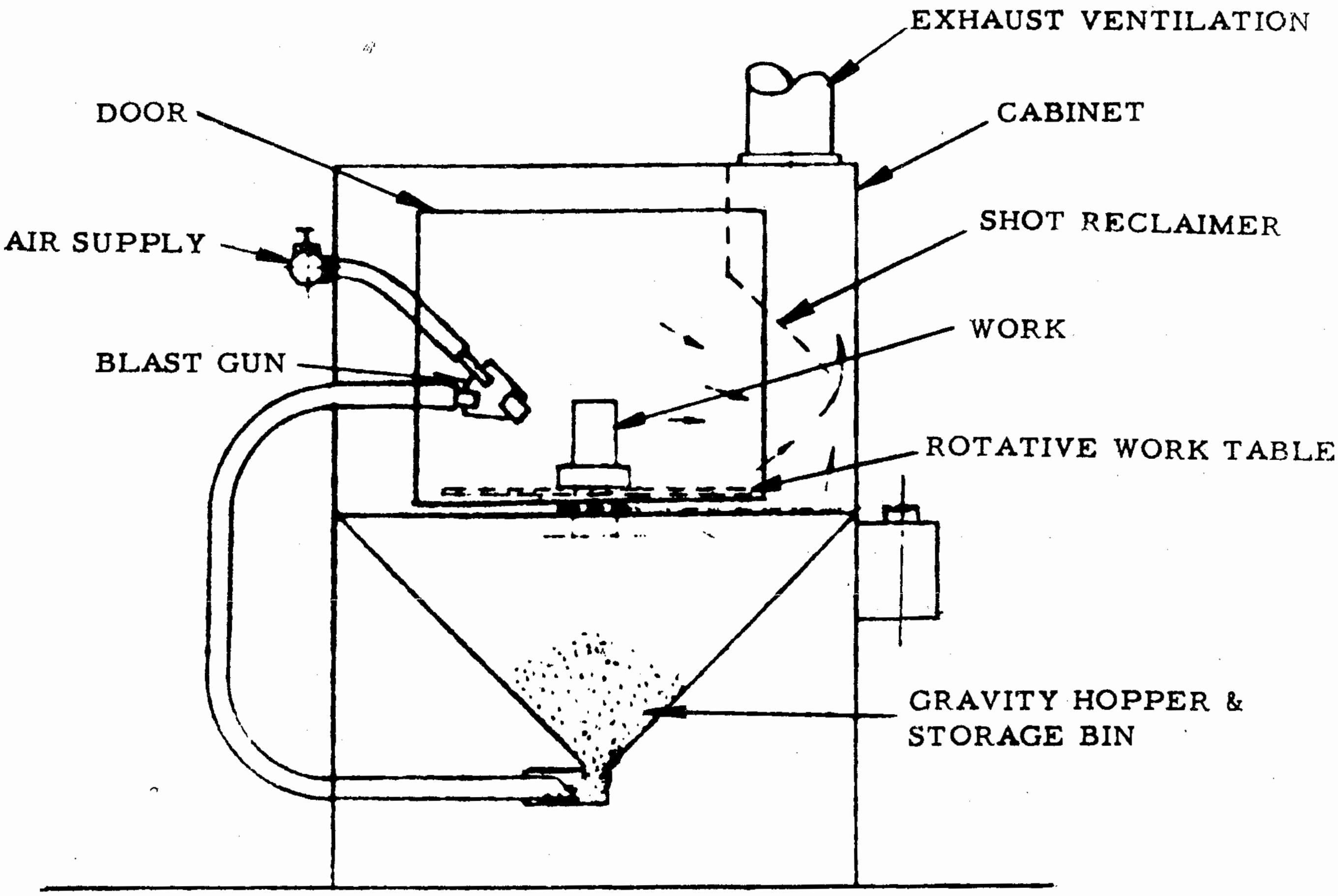
These machines have a slightly higher blast efficiency than the suction-induction type. They are used where a relatively fixed nozzle position is satisfactory and where the vacuum is not sufficient to lift shot from the lower storage bin.

The induction types have minimum air requirements.

c. Direct pressure machines (Figs. 4, 5, and 6)

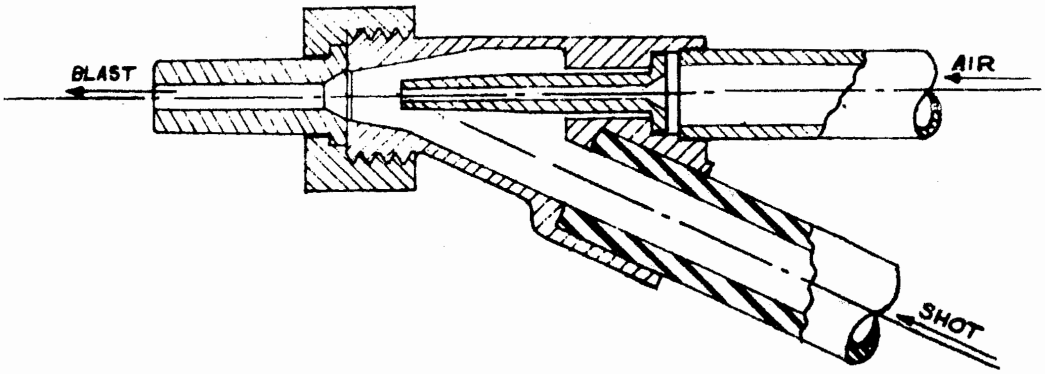
In this type of machine, the shot is stored in a pressure vessel which is maintained at the same pressure as the air blast. The shot is fed by gravity into a mixing chamber in the pressure vessel, where it is caught in the air blast and discharged through a nozzle.

This is the most elaborate type of air blast and has more flexibility, since greater nozzle movements are possible. It is used for peening small areas, such as fillets, at the higher intensities.



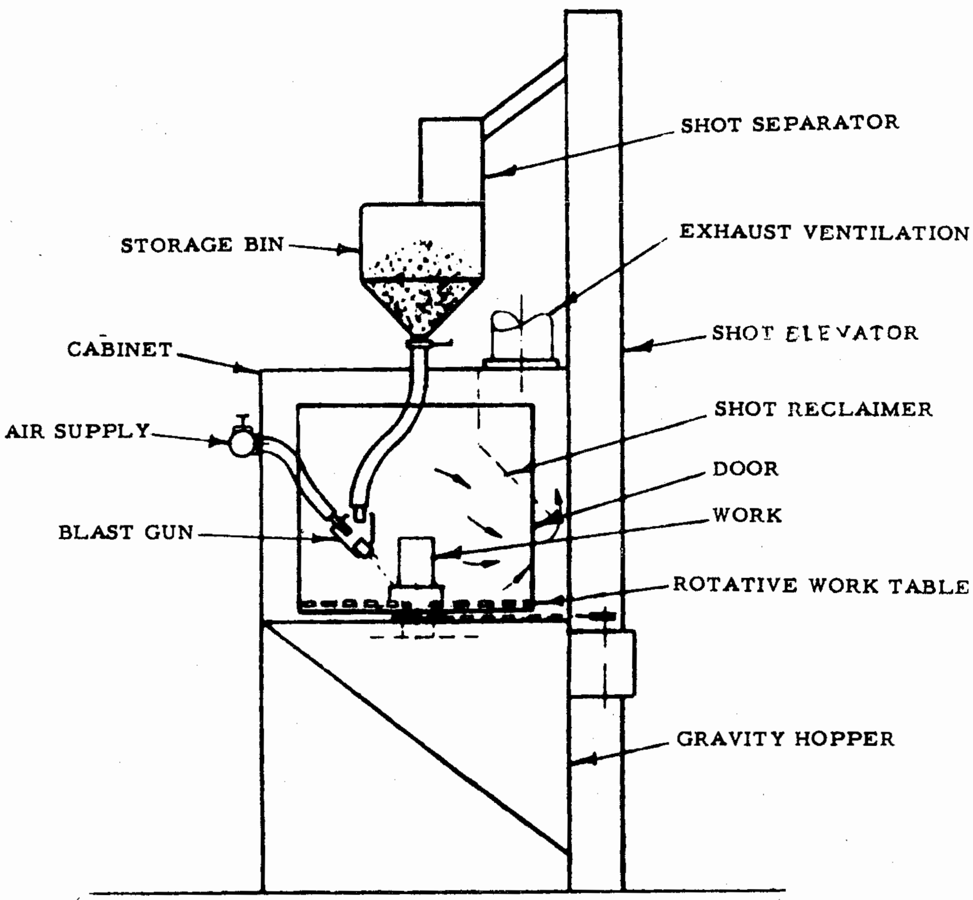
TYPICAL SUCTION - INDUCTION PEENING MACHINE

FIG. 1



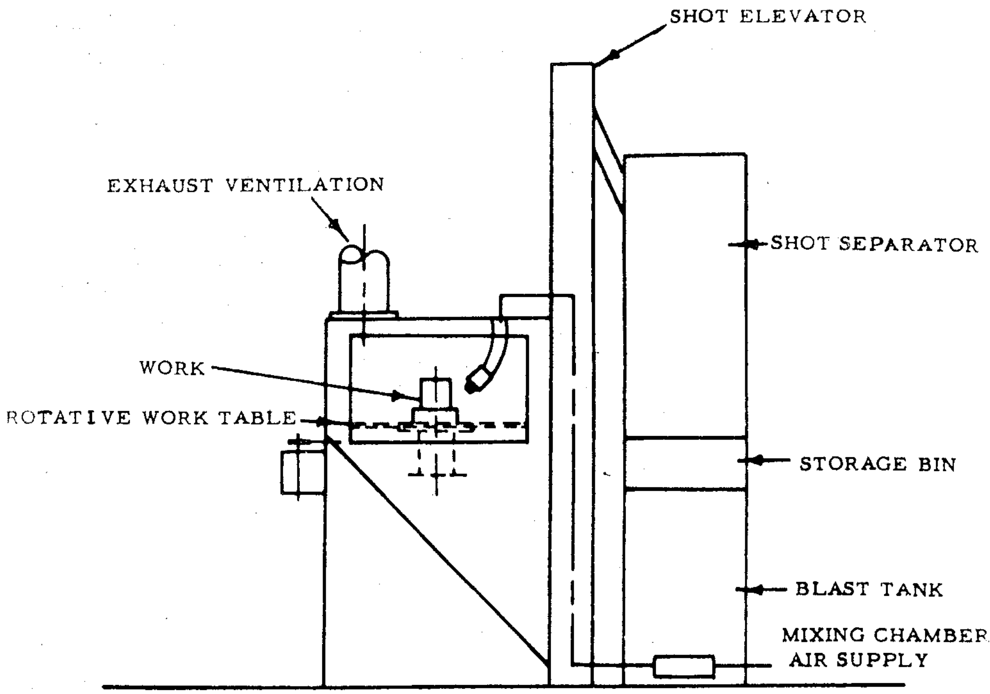
INDUCTION NOZZLE

FIG. 2



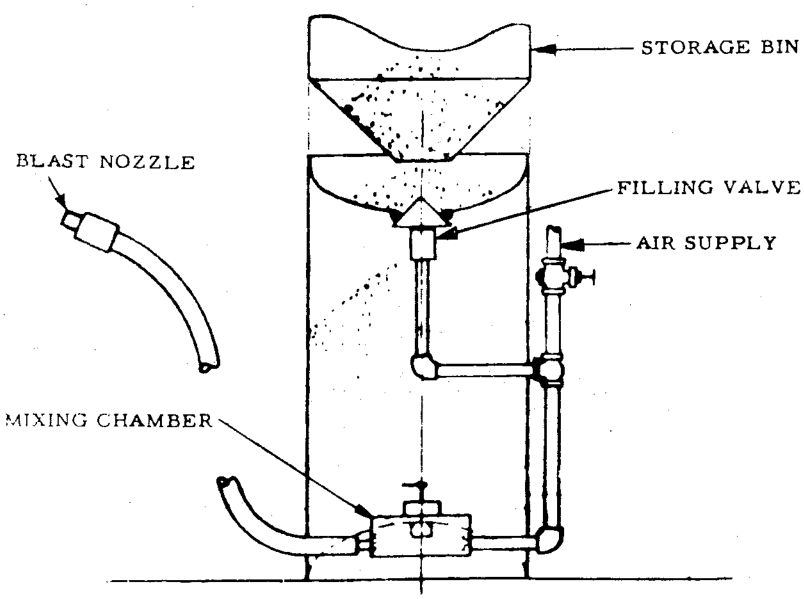
TYPICAL GRAVITY - INDUCTION PEENING MACHINE

FIG. 3



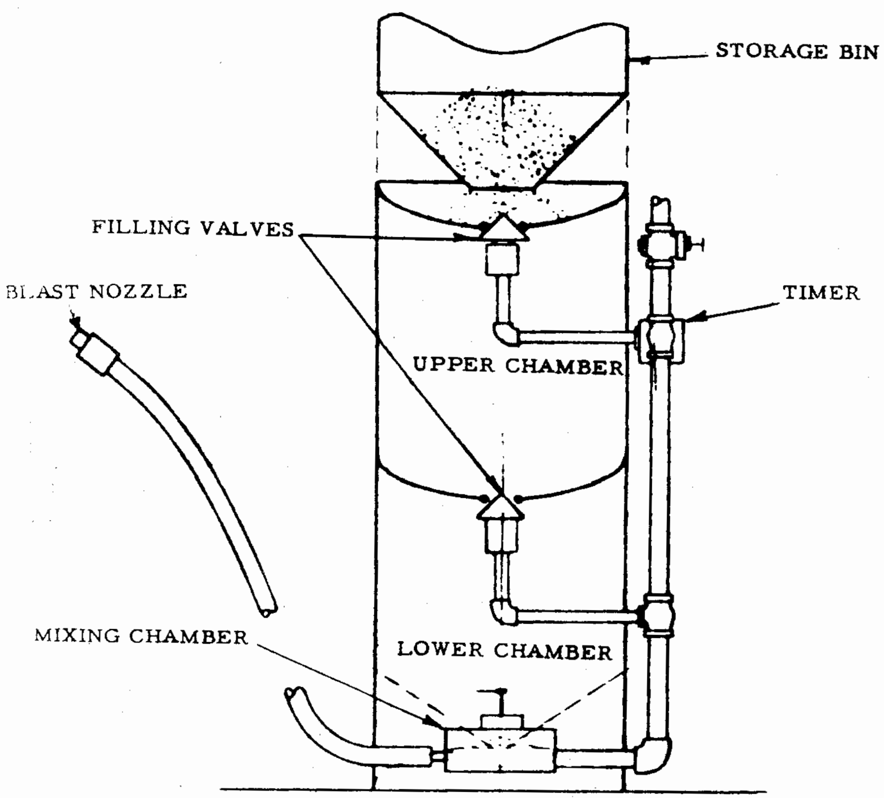
TYPICAL DIRECT PRESSURE PEENING MACHINE

FIG. 4



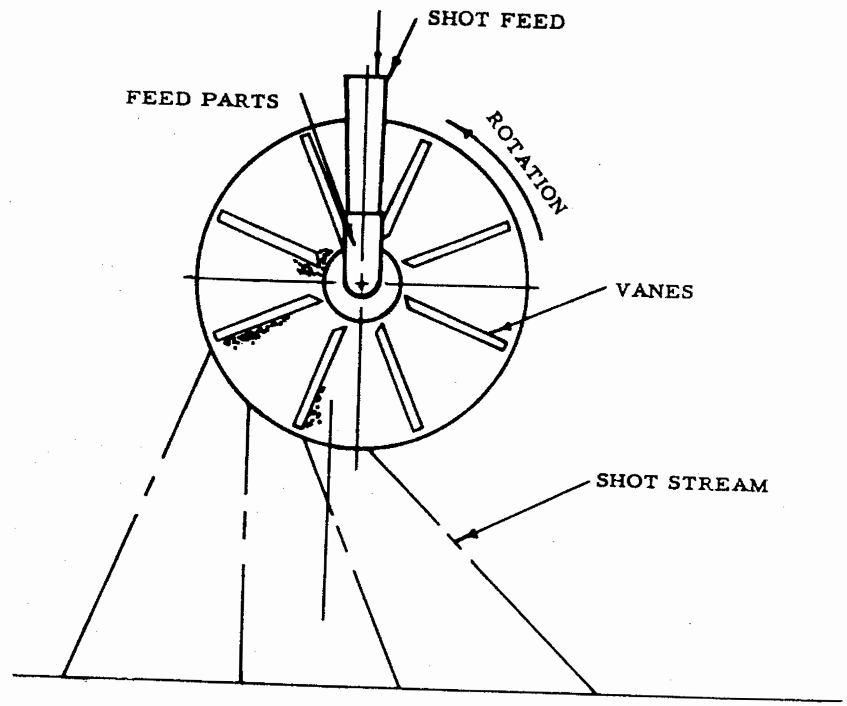
PRESSURE BLAST TANK
(INTERMITTENT FILLING)

FIG. 5



PRESSURE BLAST TANK
(CONTINUOUS FILLING)

FIG. 6



CENTRIFUGAL WHEEL PEENING EQUIPMENT

FIG. 7

Nozzles

In all three types of air blast machines, the shot is discharged through a nozzle which is expendable, due to the abrasive action of the shot. The life is dependent upon the composition of the nozzle and of the material flowing through it. "Long life" nozzles have added advantage of providing a uniform shot stream because of the nearly constant orifice size.

It is important in air machines to provide a good pressure regulator and water trap in the compressed air line because any condensation which is admitted to the shot supply tends to "freeze" the shot into a solid mass.

2. Centrifugal Blast Machines (Figs. 7 & 8)

In this class of machines, the shot is propelled by centrifugal force. The shot is gravity fed to the hub of a rotating wheel, which has radial vanes or blades. By means of a control unit, the shot is directed onto the blades of the wheel, whence it is thrown in a fan-shaped stream by centrifugal force.

In cases where flat work is to be peened, this fan-shaped stream should be as concentrated as possible for efficient peening. The desired direction of the blast is obtained by an angular adjustment of the control unit which is stationary during the operation of the wheel.

WORK HANDLING

In order to obtain as uniform peening as possible, various handling devices have been developed to present the surface to the shot stream.

1. Single Rotary Table

The principle of operation of this type of machine involves a table rotating on a vertical axis in a fixed position as illustrated in Fig. 9 which shows a hub being shot peened. The hub is located on the center of the table so that the fillet will be peened uniformly.

2. Rotary Table - Straight Line Travel

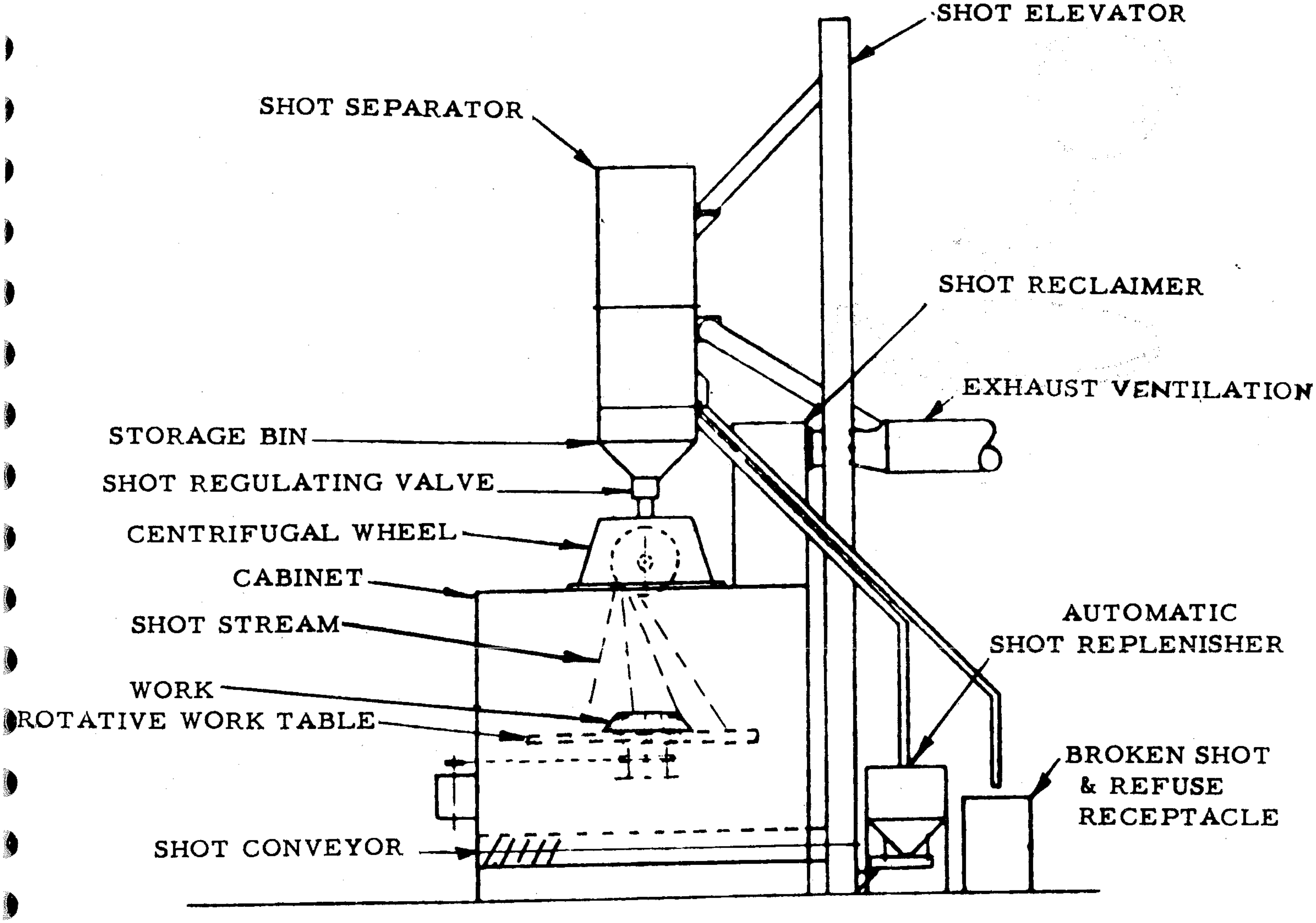
In this type of machine, a rotating table travels through the blast in a straight line, as shown in Fig. 10. The illustration shows a steering knuckle being shot peened. The straight line travel permits concentration of the blast stream on the center of the table throughout the length of the blast.

3. Rotary Table - Circular Travel

In this type of machine, the rotating table travels in a circular path, as illustrated in Fig. 11, in which a bevel gear is being peened. The blast is positioned so that the desired coverage is obtained on the areas of the part to be peened.

4. Angular Roll

This device involves a series of angularly mounted dished rolls to provide rotation of the work about a horizontal axis with straight line travel parallel to the axis of rotation. This movement is illustrated in Fig. 12, which shows a torsion bar being peened.



TYPICAL CENTRIFUGAL WHEEL PEENING MACHINE

FIG. 8

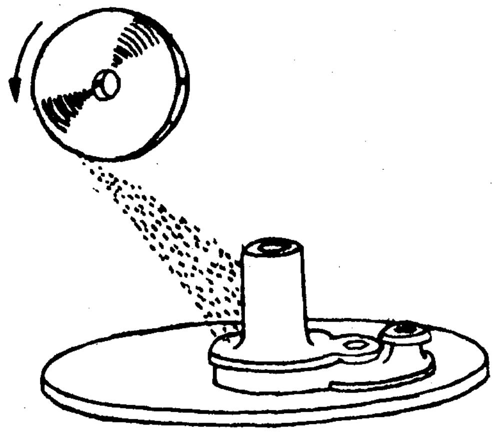


FIG. 9

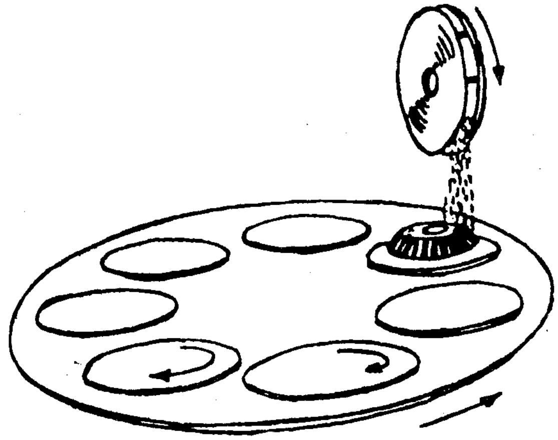


FIG. ~~10~~ 11

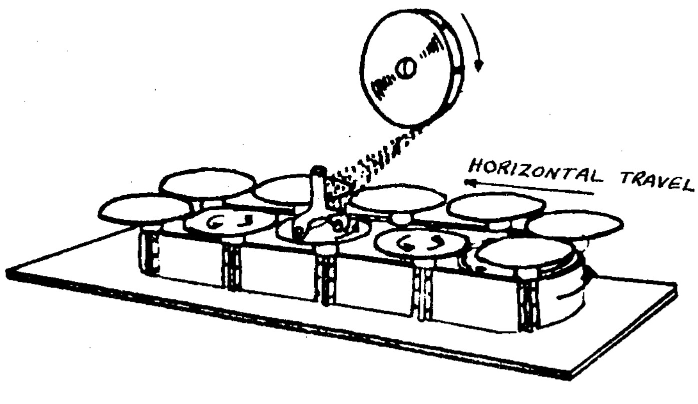


FIG. ~~11~~ 10

5. Parallel Roll

This device consists of two horizontal and parallel driven work rolls to provide a motion similar to that described above, but for shorter lengths. A feed device advances the work through the machine. Fig. 13 illustrates this motion in peening a coil spring.

6. Belt Conveyor

In this type of machine, the work travels through the machine in a straight line without rotation. The motion is illustrated in Fig. 14, which shows leaf springs being peened. The work is carried through the blast zone on an endless conveyor.

7. Tumbling Machine

In this device, the work is tumbled under the wheel blast. This type of machine may be used on small parts where high production is required.

Special Cabinets

Many peening applications will require the use of a special peening machine to fit the requirements of the particular parts to be peened, such as size and shape of parts, production requirements, etc.

Shot Handling

The enclosure, or cabinet, surrounding the shot peening equipment serves as a shield to prevent the escape of flying shot, with its accompanying hazards. It also confines the dust which is generated by the process so that, by means of a suitable outlet, the dust can be removed by a conventional dust collector.

The cabinet is also provided with a hopper in which the shot is collected after it strikes the work. From this hopper, the shot is conveyed by gravity or otherwise to an elevator which transports the shot to a separator for removal of broken shot and "fines".

The shot from the elevator enters a screen which removes any large foreign particles which might be in the system. The whole and broken shot falls through the screen and, by means of a distributing device, is deposited uniformly on an inclined plate. By means of gravity, it flows down the plate towards a storage bin, smaller particles gravitating to the underside of the mass.

A controlled air gap in the plate affects the actual separation, as the small particles and the broken shot are pulled through the gap by a regulated air flow. The whole shot, having a greater inertia, fall past the air gap and into the storage bin. Means are provided for varying the air gap and the air stream velocity, depending on the size shot used.

For a peening operation, the separator should be capable of removing broken or undersized shot. The degree to which broken particles are removed varies considerably in practice. Usually, the specific conditions for a given part are established by laboratory fatigue testing.

To maintain uniform peening conditions, shot should be added continuously. Equipment for accomplishing this is available.

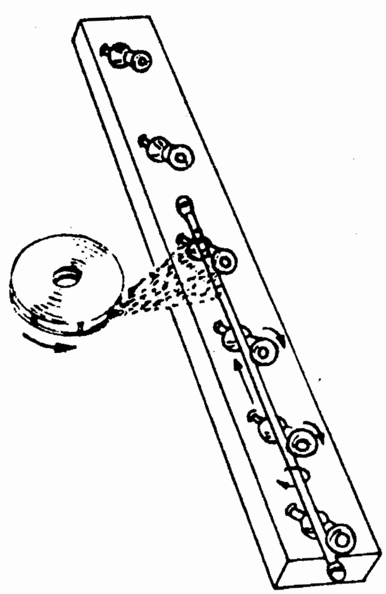


FIG. 12

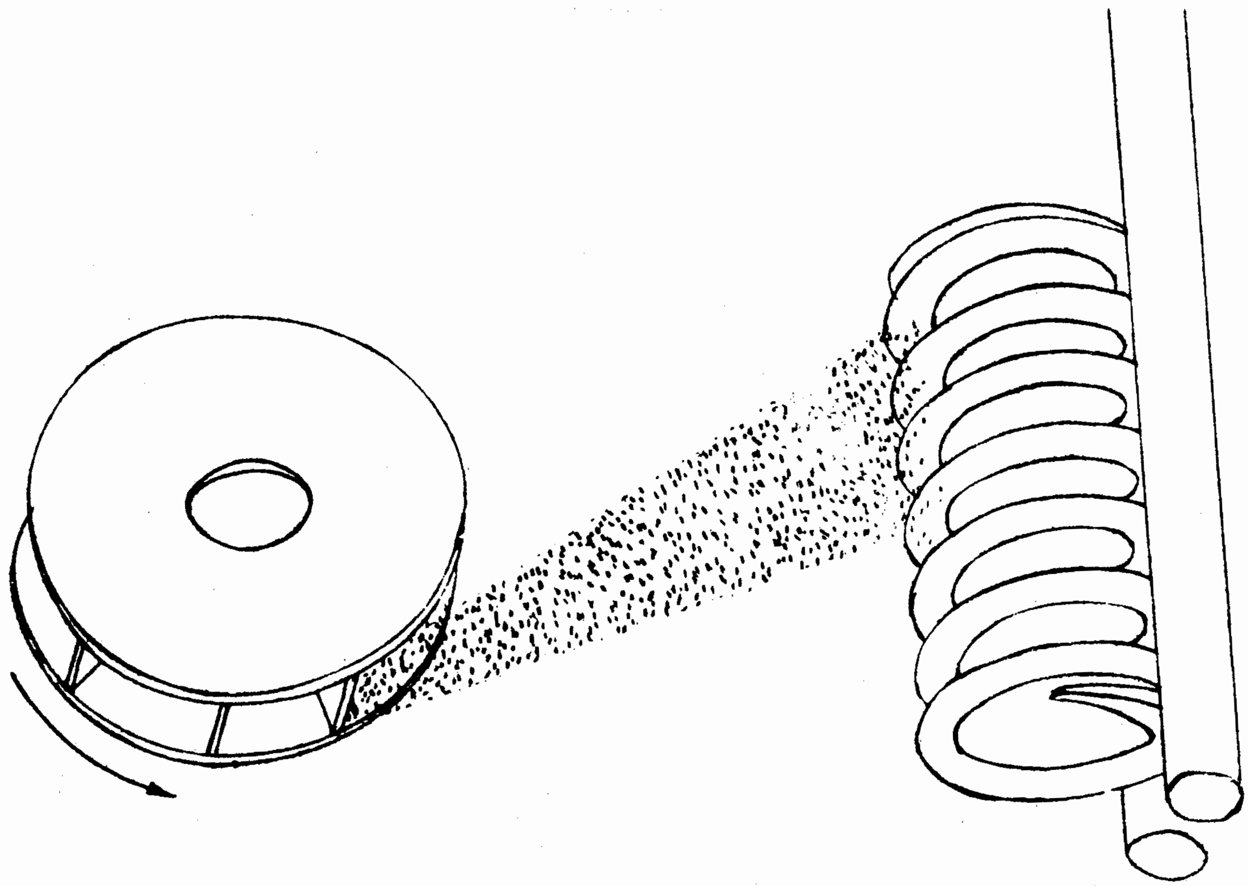


FIG. 13

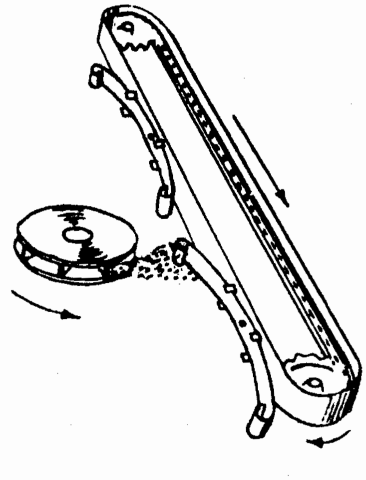


FIG. 14

IV. SHOT

The materials used for peening are generally cast iron or steel balls or short cylinders, and are known as "shot". Some non-ferrous and non-metallic materials are used for special applications.

Cast Iron Shot

The cast iron shot is made from cupola melted iron containing about 3.5% carbon and 1.5% silicon. This iron is atomized into random sizes and rapidly cooled in water to produce ball shaped particles of white cast iron, having a hardness of approximately Rockwell C63*. The random sizes are screened and separated into the different size ranges (see SAE Handbook Specification on Shot Sizes).

To reduce the hardness and increase the resistance to fracture in use, this shot may be heat-treated in various ways to produce hardnesses of Rockwell C 20 to 57, depending on the producer and use. Such material can be produced to a specified hardness range of about 8 points Rockwell.

Steel Shot

Steel shot may be either cast balls, or balls forged from wire, or short cylinders cut from wire.

Cast Steel Shot is atomized into random sizes from plain carbon and alloy steels of varying carbon content. It is screened and then heat-treated to various hardnesses, ranging from Rockwell C 20 - 60, depending on the producer and use. These shot are usually not as hard as the unheat-treated white cast iron shot, but generally have a much greater resistance to fracture in use.

Cut Steel Wire of different hardnesses and various compositions is available in cylinders (length approximately that of diameter), which wear to a spherical shape with use. They may be obtained pre-rounded, also, if desired.

Wrought Steel Shot - Steel wire of different carbon contents may be forged into spheres, as in ball bearing manufacturing, and heat-treated. This product is uniform in shape and dimensions, but is of limited use due to its high cost.

Miscellaneous Shot Types - Non-ferrous and non-metallic balls, such as copper, glass, and plastic and other organic matter, have been used for special applications on non-ferrous metals.

V. EFFECT OF SHOT PEENING

Peening is generally applied to increase resistance to fatigue failure. Fatigue failures are quite easily recognized and almost without variation emanate from a focal point at the surface. These focal points are stress raisers, such as fillets, holes, keyways, seams, laps, tool marks, stamp marks or variations in structure. When fatigue failures are encountered, the stress raisers should be removed or avoided, if possible.

*Converted from Vickers or equivalent.

Often the elimination of the stress raisers by design or fabrication is sufficient and makes further operations unnecessary. In some instances, where a high minimum fatigue life is required and the type of surfaces encountered will have defects which could be removed only at great additional expense, shot peening is employed as the most economical method of securing the necessary fatigue life.

As more detailed information about the shot peening process becomes available and is understood, more extensive consideration will be given to the process in design calculations. This is already manifested in spring and gear design.

IDEALIZED FATIGUE CURVES SHOWING THE NUMBER OF STRESS CYCLES TO CAUSE FAILURE AT VARIOUS STRESSES

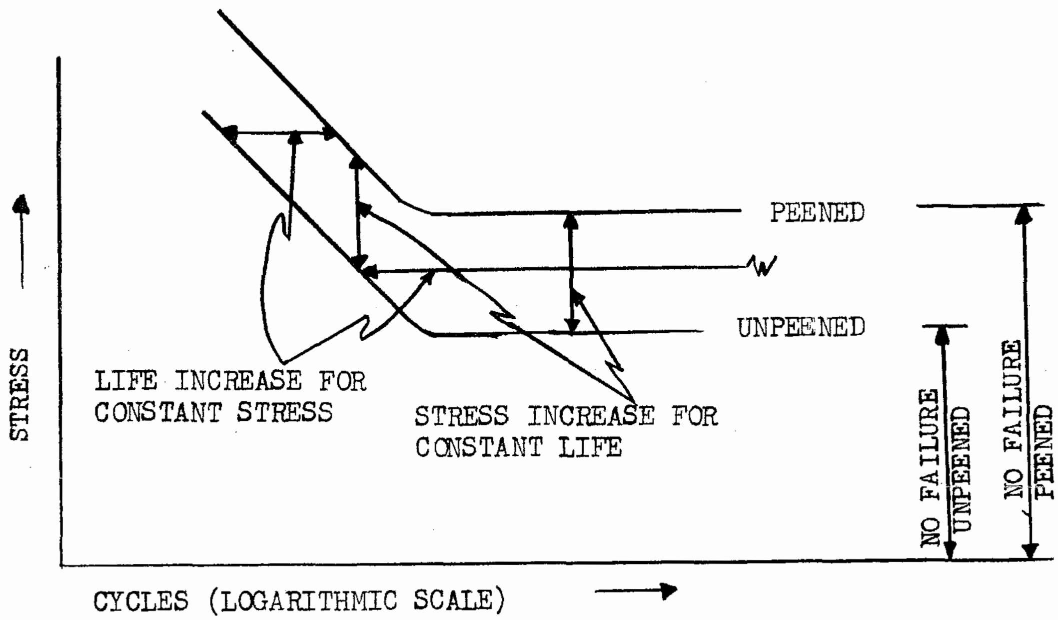


FIG. 15

The effects of shot peening (13) on the fatigue properties of parts are generally expressed in either of two ways: increase in stress for a given life, or increase in life at a given repetitive stress. These points are illustrated in Figure 15.

The increase as a definite proportion to the stress range, as shown on the usual fatigue or so-called Goodman (14) diagrams of peened and not peened material, is 50% to 100%, depending upon the material used. Thus, in tests for minimum increase in life in coil springs in sections less than 3/8", such values as the following are found for one particular set of stress ranges and particular heats of steel:

(13) and (14) Bibliography Page 42.

Material	Range Un-Peened	Range Peened	% Increase
Carbon Spring Steel, SAE 1074	75,000 psi	115,000 psi	54%
Alloy Spring Steel, SAE 6150	70,000 psi	115,000 psi	60%
Stainless Steel, Type 302	45,000 psi	90,000 psi	100%
Phosphor Bronze, SAE 81	15,000 psi	30,000 psi	100%

On larger spring sections with metallurgically sound material, similar values hold. It must be realized that even as small an increase as 10% in the fatigue range could take an axle shaft or spring, which was just on the border line in giving failures and make it very successful, so that the percent of increase over the previous life might be several thousand percent. This fact should be kept in mind when increases in life are given. Exact diagrams are not available for all materials in either torsion or bending. Hence, an increase is determined as an increase in the part life. This may be due to several factors other than peening; for instance, better lubrication due to roughening which forms oil pockets, or an actual radius change in a fillet, both possible under normal peening conditions.

With the foregoing explanation, several examples of peening effects may be of interest. The railway spring industry reports increases in life due to peening of 438% to 1150%. Shot peening increases the fatigue life of gears to such an extent that gears which, unpeened, failed in 50 hours were running under the same conditions in perfect shape at 250 hours, or a clear increase of 500%. Other tests on drive pinions give from 40% to 414% life increase with peening. Steering knuckles show up to 121% increase in cycles to failure after peening, while crankshafts gave 100% to 1000% increase in life at the same loads. In many instances, satisfactory transmission or rear axle gears are shot-peened and then the loads increased so that they can be used on heavier cars and equipment. These increases vary with design from 17% to 50% and constitute a marked saving in material and space. This is one of the important effects of shot peening which design engineers are just beginning to use.

VI. PRODUCTION PROCEDURE

Method of Control (49)

The control of a peening operation is primarily a matter of control of the properties of the blast of shot in relation to the work being peened. This involves the periodic measurement of "intensity", which measures the properties of the blast of shot and "coverage" which involves exposure.

If a flat piece of steel is clamped to a solid block, and exposed to a blast of shot, it will be curved upon removal from the block. The curvature will be convex on the peened side. The extent of this curvature on a standard sample serves as a means of measurement of the blast. The degree of curvature depends upon the properties of the blast, the properties of the test strip, and the nature of exposure to the blast, as described below.

Properties of the blast are the velocity, size, shape, density, kind of material, and hardness of the shot.

The properties of exposure to the blast are the length of time, angle of impact and shot flow rate.

(49) Bibliography Page 44.

The properties of the test strip depend upon the physical dimensions and mechanical properties of the strip.

Based on these principles, the SAE has adopted the following standards: Test strips, holding block and gage. Specifications of these parts, the method of use, and a standard designation are presented herein.

SPECIFICATIONS OF INTENSITY MEASURING EQUIPMENT

Test Strips and Holding Fixtures:

Standard test strips "A" and "C" are shown in Figure 16, while the test strip holder is shown in Figure 17. The relationship between test strip "A" and Test Strip "C" is shown by Figure 18, which shows "A" and "C" strip readings for conditions of identical blast and exposure.

Gage:

The gage for determining the curvature of the test strip is shown in Fig. 19. The curvature of the strip is determined by a measurement of the height of the combined longitudinal and transverse arcs across standard chords. This arc height is obtained by measuring the displacement of a central point on the non-peened surface from the plane of four balls forming the corners of a particular rectangle. (This gage is commonly referred to as Almen No. 2 Gage.) To use this gage, the test strip is located so that the indicator stem bears against the non-peened surface.

Designation Standard of Intensity Measurements:

The standard designation of intensity measurement includes the gage reading or arc height and the test strip used. It may be explained by the following example:

Gage Reading → .013A ← Test Strip

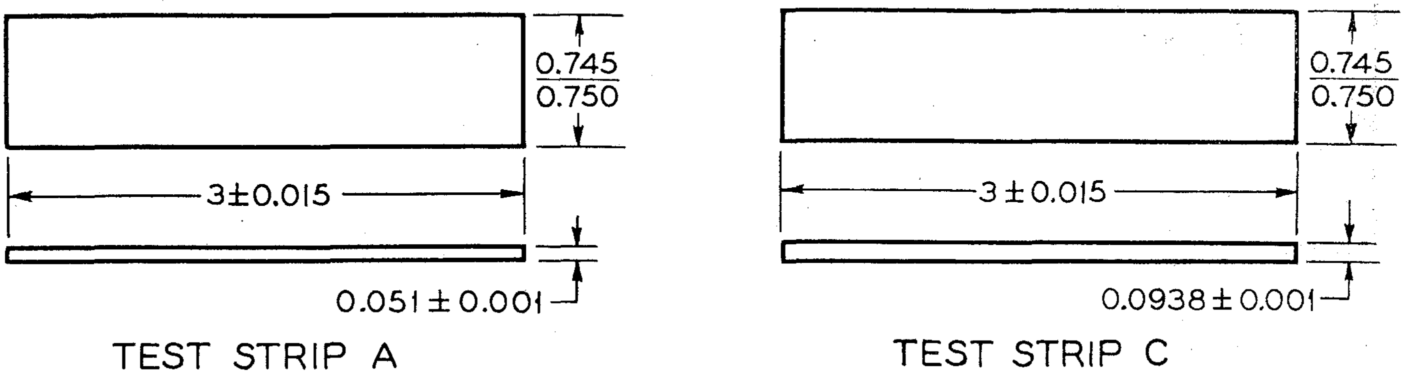
This example signifies that the arc height of the peened test strip as measured on the gage is .013" and the test strip used is of the "A" size, always assuming that the measurement was made on the standard Almen No. 2 gage.

.006 - .008 C

This signifies .006" to .008" gage reading on "C" size test strip measured with the same gage. This example is typical of the method used for specifying an arc height tolerance for an application. As shown in both of the examples, the gage or arc height reading is given first and is followed by the test strip designation.

Recommended Practice:

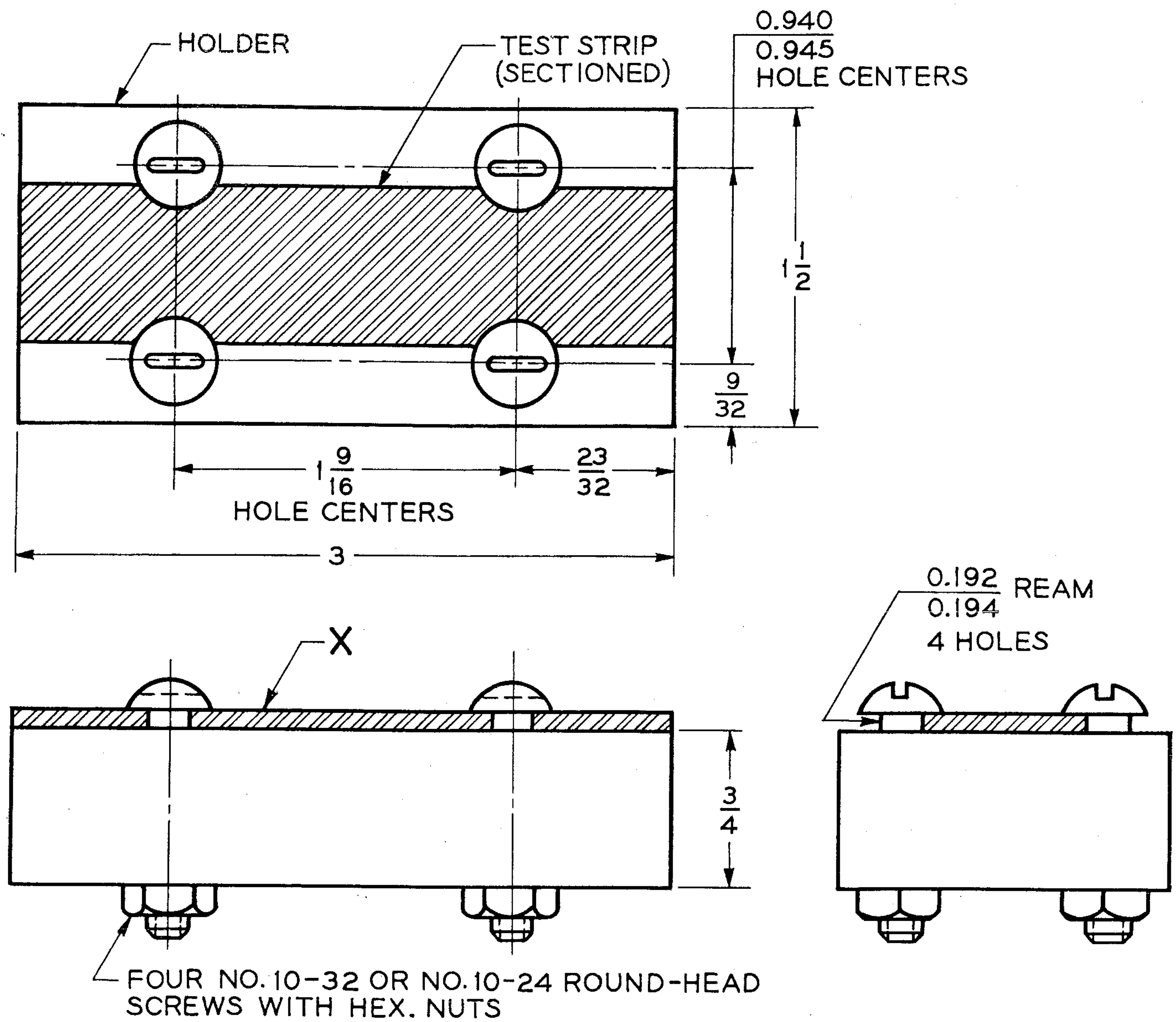
The test Strip A is used for arc heights up to .024 A, and, for greater degrees of peening, the C Test Strip is used.



Analysis of Stock - SAE 1070
Cold Rolled Spring Steel
Square Edge Number One (on 3" edges)
Finish - Blue Temper (or Bright)
Uniformly hardened and tempered to 44-50 RC
Flatness - ±.0015" arc height as measured on a standard Almen #2 gage

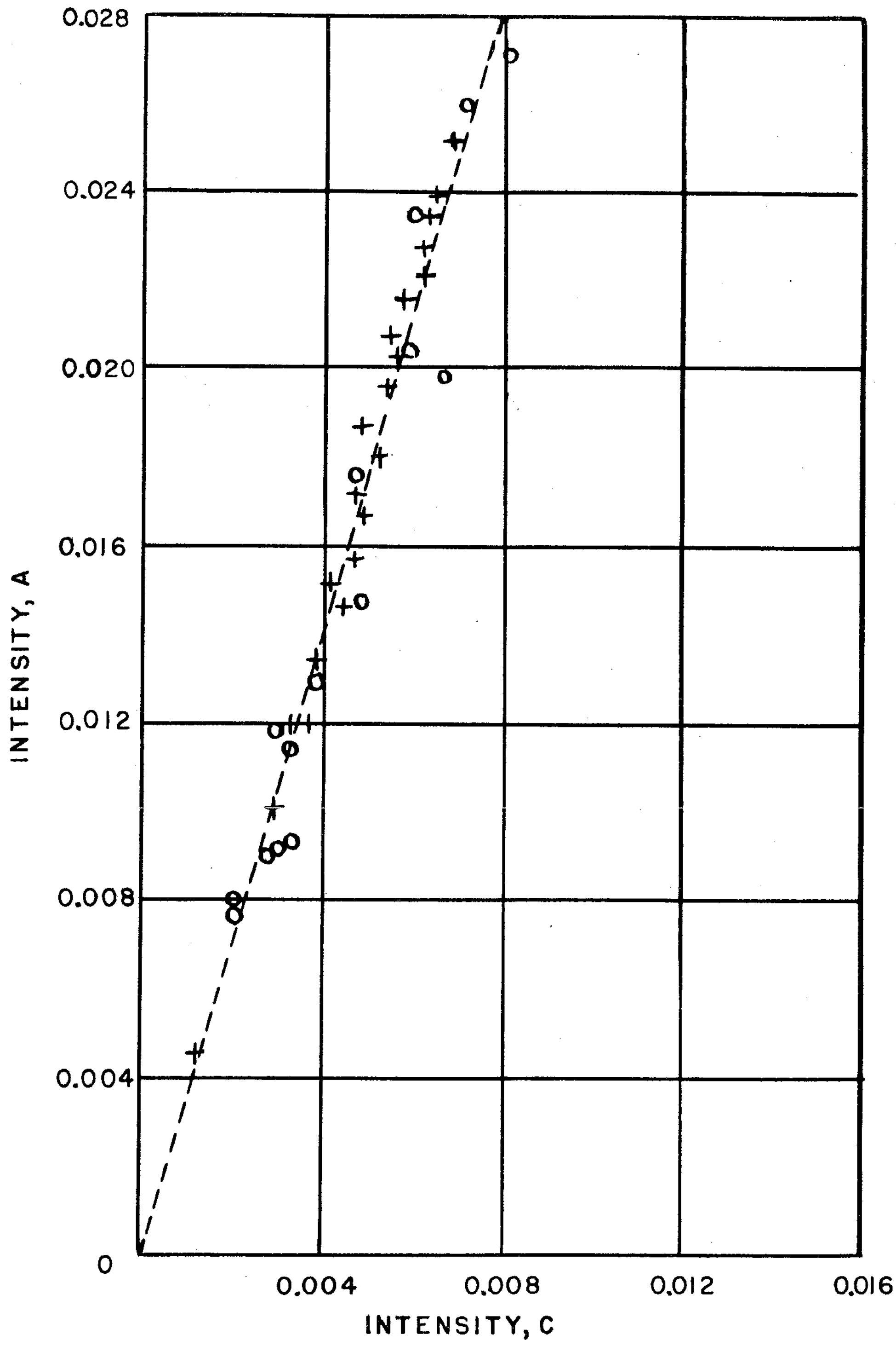
TEST STRIP SPECIFICATIONS

FIG. 16



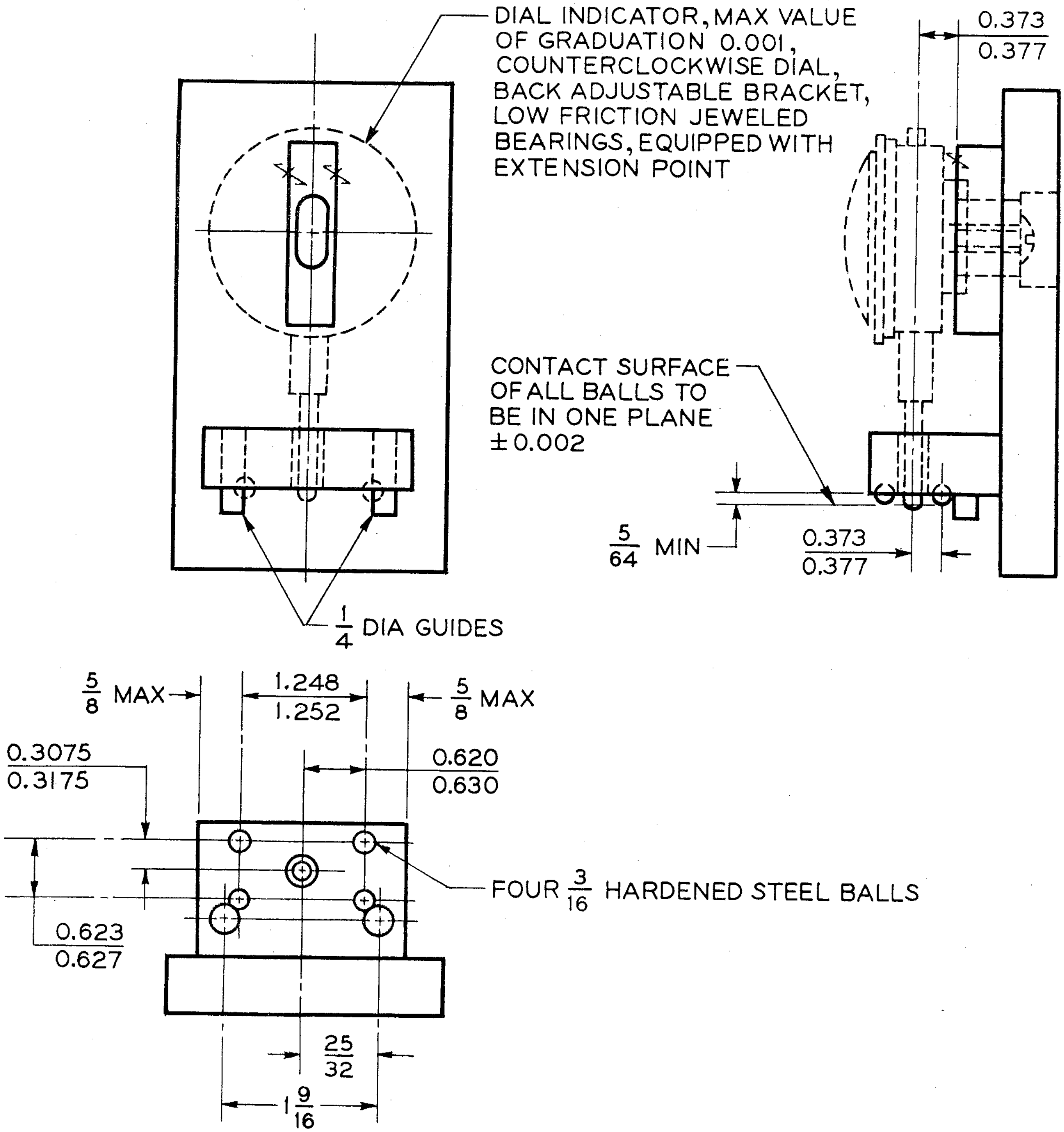
ASSEMBLED TEST STRIP AND HOLDER

FIG. 17



CORRELATION OF "A" AND "C" STRIPS AS CHECKED
ON AN ALMEN #2 GAGE

FIG. 18



GAGE (ALMEN GAGE #2)

FIG. 19

METHOD OF USE OF INTENSITY MEASURING EQUIPMENT

METHOD NO. 1 - Procedure:

The general procedure may be outlined as follows:

a. Fasten the Strip A (or C) tightly and centrally to the Test Strip Holder.

b. Expose the surface "X", Fig. 17, of the strip to the blast to be measured. Record the time of exposure, or its equivalent.

c. Remove the strip from the holder and measure the arc height on the gage. The zero position of the gage must be frequently checked and, if necessary, adjusted.

d. Using different exposure times, repeat a, b, and c sufficiently to determine a curve similar to Fig. 20.

e. The gage reading corresponding with the point "A" where the curve flattens out is generally taken as the intensity measurement of the blast of that particular peening. In some cases, this point is difficult to pick out, and requires some judgment.

Production Set-Up Procedure - Intensity Measurement:

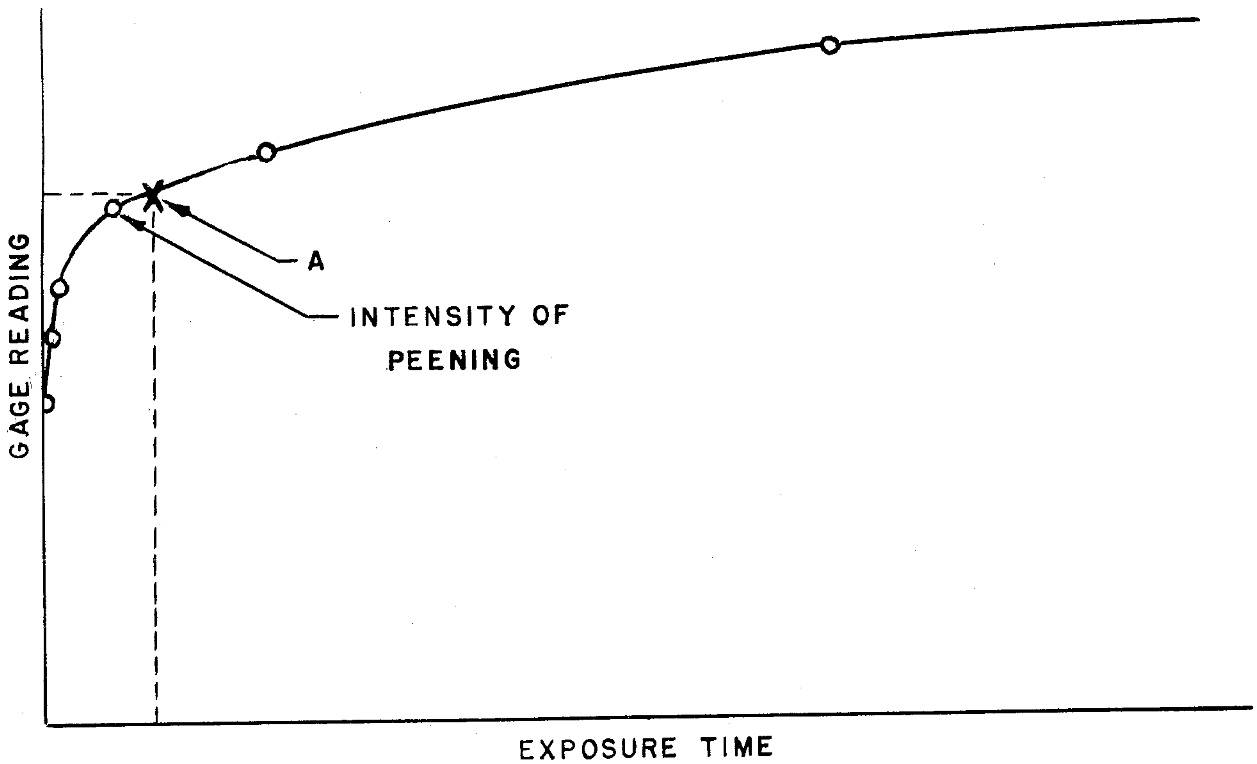
The procedure to be used in making a production set-up, in which a setting of the machine is to be determined for an intensity found to give necessary fatigue characteristics with a definite size and kind of shot, may be described as follows:

a. Provide a fixture to support the test strip in a manner to simulate the most critical surface of the part to be peened. In cases where more than one critical surface is to be peened, the fixture should provide for the mounting of the required additional test strips.

b. With an estimated setting of the machine (shot flow rate, shot velocity and type of shot), a series of test strips should be exposed to the blast of shot, each for a different exposure time, so that a curve, such as shown by Fig. 20, may be established.

c. If the intensity measurement obtained from the curve does not fall within the desired limit, machine settings must be changed. If a higher arc height is desired, either higher shot velocity or larger shot is necessary, assuming a given type of shot. If lower arc height is desired, a lower shot velocity or smaller shot is needed. These velocity changes may be made by changing wheel speed or air pressure. In certain cases, an adjustment may be made in the direction of the shot stream, but the most efficient peening is obtained with the direction of the main part of the blast stream normal to the critical section of the part being peened.

d. After new settings are made, arc heights are again determined as described in "b" above.



INTENSITY DETERMINATION CURVE

FIG. 20

e. Suppose, with the first trial, the curve B of Fig. 21 was obtained and the desired arc height is as indicated by the horizontal broken line. The shot velocity or shot size is, accordingly, too great and one or both must be reduced. Suppose the second trial resulted in the curve C. Here the shot velocity or shot size is too small. Perhaps the third trial would result in curve D, which is the correct one for the required intensity.

f. When the machine settings are found that yield the desired intensity, the time of exposure of the part is also indicated. For example, on curve D, Fig. 21, the time of exposure T, corresponding with point Q on the curve, is that which would ordinarily be used.

g. Most important of all, run a fatigue test on the part under consideration. The arc height is useful to keep a machine at a known operation level, and may not be indicative of fatigue life. It may be necessary to reset the machine until satisfactory fatigue life is obtained.

METHOD NO. 2 - Procedure:

The general procedure may be outlined as follows:

a. Fasten the strip "A" (or "C") tightly and centrally to the test strip holder.

b. Expose the surface "X", Fig. 17, of the test strip to the blast to be measured. Record time of exposure or equivalent.

c. Remove the strip from the holder and measure the arc height on the gage. The zero position of the gage must be frequently checked and, if necessary, adjusted.

Coverage

The degree of coverage can be determined as follows:

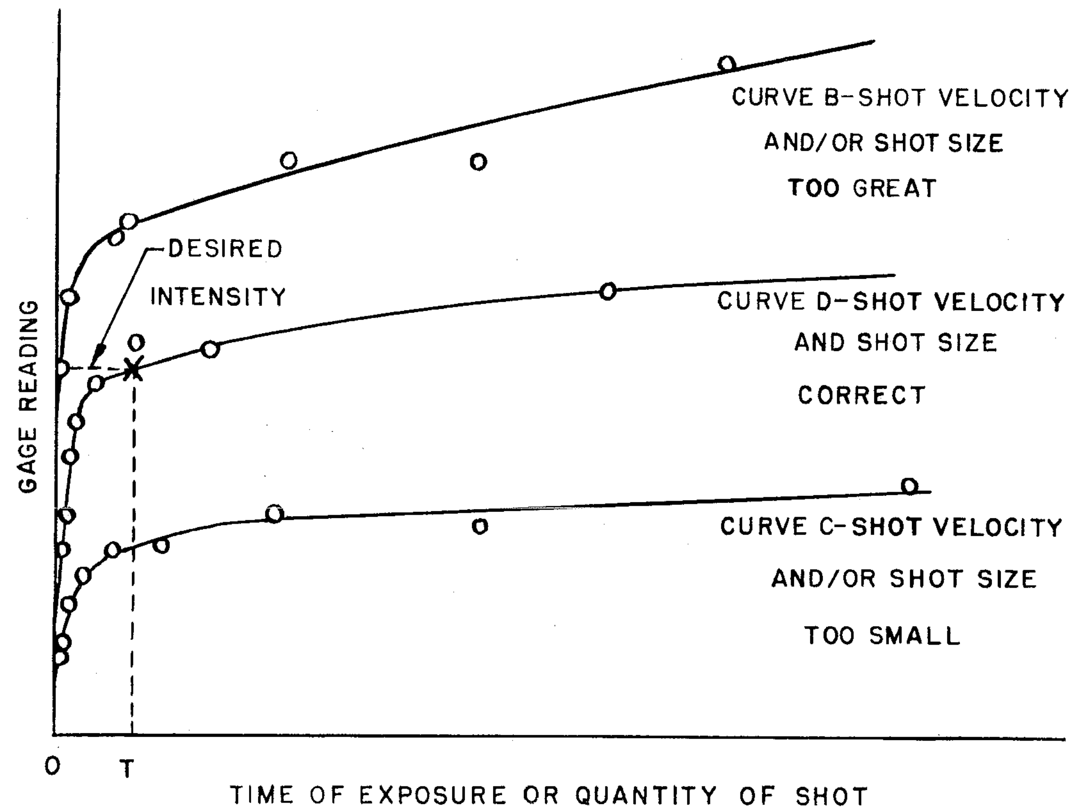
a. Polish the strips "A" (or "C") to obtain a reflecting surface by means of metallurgical polishing cloths, or equivalent.

b. Fasten to the test strip holder.

c. Expose the polished surface to the blast under conditions identical to that used in determining the arc height of Almen Gage reading.

d. Remove the strip from the holder and place it in the field of a metallurgical camera.

e. Using a piece of transparent paper as ground glass, and with a magnification of approximately 50 diameters, trace the indented areas with a sharp pencil. The indented areas can be identified by the contrast of the polished surface and the inclined surfaces of the indentations.



INTENSITY DETERMINATION CURVES FOR LIKE HARDNESS

FIG. 21

f. Measure with a planimeter the area of all of the indentations enclosed by a circle of known diameter. The ratio of the indented areas to the total area is the percentage coverage.

Relationship of Coverage to Exposure Time:

There is a definite and quantitative relationship between coverage and exposure time. This relationship may be expressed as follows:

$$C_2 = 1 - (1 - C_1)^n$$

C_2 = % Coverage (Decimal) after n cycles.

C_1 = % Coverage (Decimal) after 1 cycle.

n = Number of cycles.

As this expression indicates, coverage approaches 100% as a limit. It is difficult to obtain accurate measurements of coverage above 98%, but a measurement at a lower degree of coverage will serve as a means of determining the exposure time or equivalent required to obtain any desired coverage. Since coverage approaches 100% as a limit, and since actual measurement can be made up to and including 98%, 98% is arbitrarily chosen to represent full coverage. Beyond this value, the coverage is expressed as a multiple of the exposure time required to produce 98%. For example, 1.5 coverage represents a condition in which the specimen has been exposed to the blast 1.5 times the exposure required to obtain 98% coverage. A chart plotted to a convenient exposure time scale is shown in Fig. 22. Due to a difference in shape or hardness, it is possible that the coverage of a test strip will not be the same as the coverage of the actual part.

Production Set-Up Procedure - Blast Measurement:

The procedure to be used in making a production set-up in which a setting of the machine is to be determined for an arc height found to give necessary fatigue characteristics with a definite size and kind of shot may be described as follows:

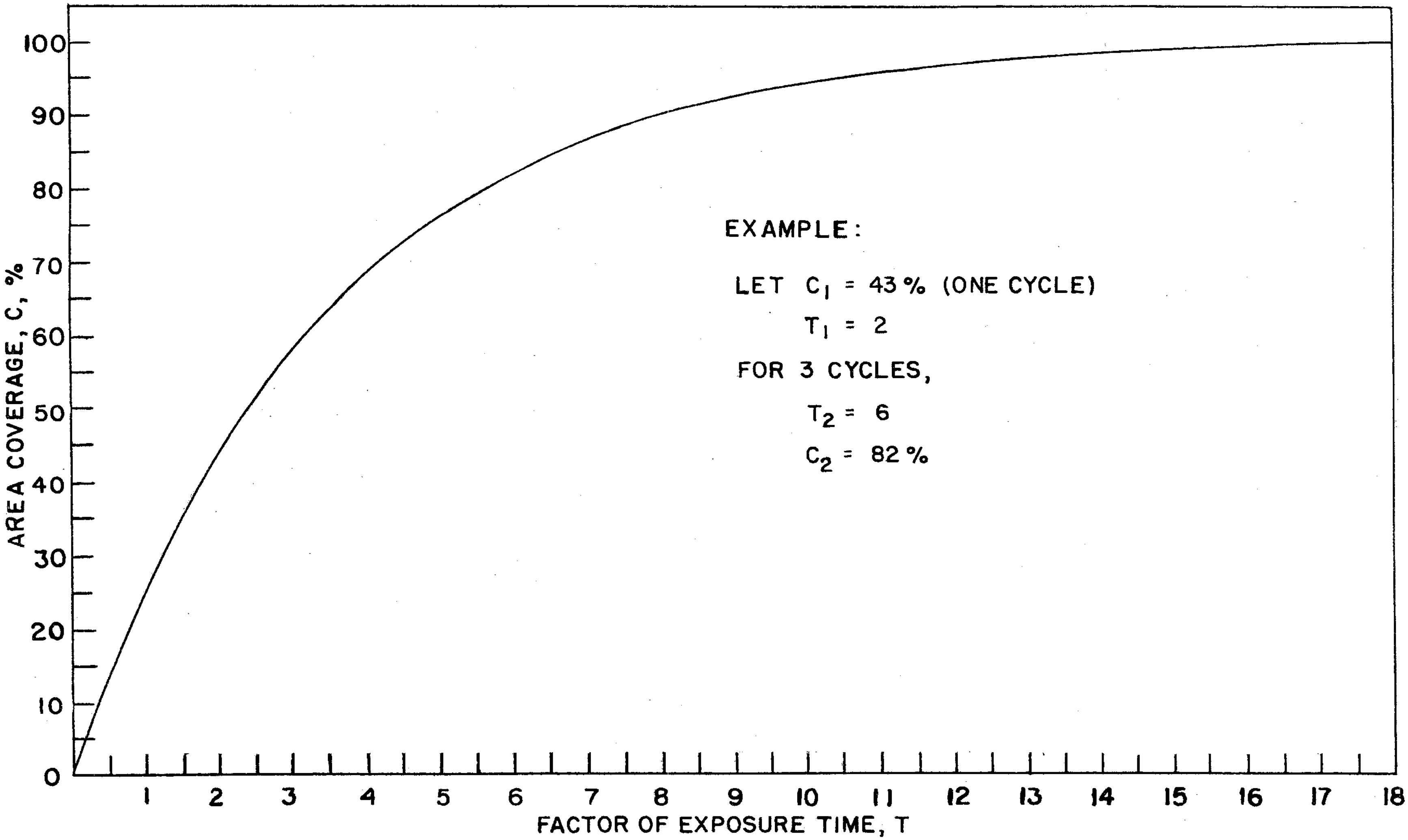
a. Provide a fixture to support the test strip in a manner to simulate the most critical surface of the part to be peened. In cases where more than one critical surface is to be peened, the fixture should provide for the mounting of the required additional test strips.

b. With an estimated setting of the machine (shot flow rate, shot velocity and type of shot), under which a low degree of coverage is expected, a polished strip should be exposed to the blast of shot for a definite exposure time or its equivalent.

c. The strip is then removed from the block and the coverage measured.

d. From this measurement of coverage, the required exposure time is calculated to produce the desired coverage.

e. A regular test strip (not polished) is then exposed to the blast for a time indicated by the coverage calculation.



100
90
80
70
60
50
40
30
20
10
0
AREA COVERAGE, C, %
EXAMPLE:
LET C_1 = 43 % (ONE CYCLE)
T_1 = 2
FOR 3 CYCLES,
T_2 = 6
C_2 = 82 %
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
FACTOR OF EXPOSURE TIME, T

FIG. 22

f. If under these conditions the blast measurement thus obtained does not fall within the desired limits, machine settings must be changed. If a higher arc height is desired, either higher shot velocity or larger shot is necessary, assuming a given type of shot. If a lower arc height is desired, a lower shot velocity or smaller shot is needed. These velocity changes may be made by changing wheel speed or air pressure. In certain cases, an adjustment may be made in the direction of the shot stream, but the most efficient peening is obtained with the direction of the main part of the blast stream normal to the critical section of the part being peened.

g. Suppose, for example, the desired conditions are .010 A and 98% coverage. Suppose further that the coverage as measured in the first trial was 76%. Referring to the chart of Fig. 22, the exposure time used in this test is equivalent to 5 units. Ninety-eight per cent would be obtained at 14 units. Therefore, the exposure time must be increased in the ratio of fourteen over five, or 2.8 times the exposure used in the first trial. This is the exposure time to be used in determining the intensity.

h. If the arc height does not fall within the desired limits, the above process is repeated with blast conditions changed as described in (f) above.

SURFACE REPLICA METHOD:

After a part has been shot peened, a transparent replica of the surface can be readily made. This replica can then be compared with other replicas, having various degrees of coverage, by projection on a screen. Acceptable and unacceptable standards can be established for the particular operation.

VALENTINE'S METHOD FOR DETERMINING THE EFFECT OF PEENING: (47)

When parts to be peened are of varying cross-section or contour, as for example a rocker arm, it is difficult to study the peening intensity distribution over the complex surface.

An ingenious method of determining the effect of peening in such cases is described in detail by Valentine in Trans. ASM Vol. 40, 1948, p. 420-434.

In brief, a duplicate of the piece being studied can be made from low carbon steel of a specified carbon range, subjected while in the soft condition to the proposed peening cycle and then annealed in a described manner to produce a recrystallization and grain growth. The piece may then be cross-sectioned in any plane and studied under the microscope. The extent of peening will be shown by the degree of grain growth in the various parts of the piece and will be in proportion to the intensity of the peening blast to which the area was subjected.

WHEEL SHOT PATTERN:

When setting up a new machine and periodically during its use, the wheel shot pattern should be checked.

(47) Bibliography Page 44.

This is done by placing a suitable piece of sheet steel at the same height and in the same position as the work to be peened and exposing to the shot blast for a few seconds. Remove and examine the sheet. If the longitudinal centerline of the shot pattern, as shown on the sheet steel, is not in the center of the work, shift the work location or check wheel alignment. This location of the pattern along the sheet may be adjusted at the wheel by loosening and turning slightly the control cage or guard deflector.

An additional check for wheel shot pattern makes use of a series of Almen strips and holders. These holders can be mounted on a bar of steel at regular intervals. The entire assembly of mounted holders and strips is placed under the wheel in a manner similar to that for the sheet steel described above. The conveyors or tables in the machine are kept stationary and the strips are exposed to the blast for a short period of time (a few seconds has been found to be satisfactory). The resulting arc heights are examined and the effective peening area can be determined. This method is useful in determining the location of the "hot spot" in the machine. Fig. 23 shows schematically how the assembly of Almen strips and holders is used.

STABILIZATION

Peening shot, whether it be white iron, malleable iron, steel or other material, is subject to failure in use just as the same materials are subject to fatigue when fabricated into structural members.

Each individual shot has a stress placed upon it at each impact which will vary in magnitude with the mass and the velocity of the shot and the hardness of the work being peened. Under repeated impact, the shot will fail.

Shot should be added to a peening machine uniformly to replace particles rejected by the separator or dust collector and other losses in order to maintain a consistent size distribution.

MASKING

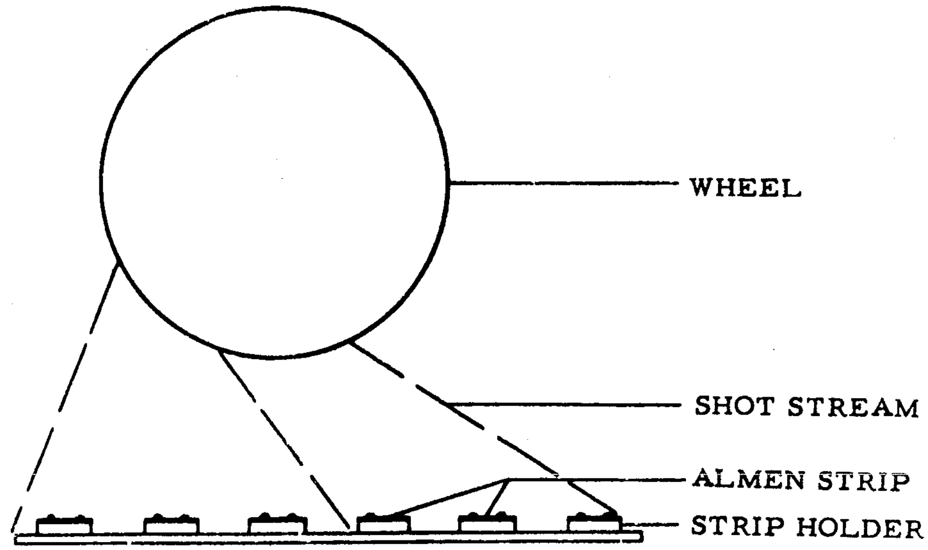
It is necessary in some instances to restrict the area to be exposed to the peening blast. This is especially true where an area to be peened is directly adjacent to a ground bearing or a threaded section, and the section receives no further machining operations subsequent to shot peening.

Masking can be done in a number of different ways, depending upon the economic considerations involved in the production set-up.

Masking tape, rubber tape (of the electrician's type) moulded rubber masks, steel protectors, and combinations of two or more of these have been successfully used.

SUPPORTING FIXTURES

In designing fixtures for the support of parts which are to be shot peened, the primary consideration is to position the part in such a way that the shot stream strikes the area to be peened so as to produce the desired results.



METHOD OF MEASURING WHEEL SPRAY PATTERN

FIG. 23

Insofar as possible, the shot stream should strike the part in a plane perpendicular to that of the peened area. Where large areas or entire parts are to be peened, it is necessary to rotate, impart a reciprocating movement, or in some instances use a combination of the two in order to obtain full exposure to the shot stream.

Every part to be shot-peened presents a different problem in handling during the shot peening operation and the solution of the problem will depend upon the equipment available and the economics of the particular application.

VII. THEORY OF STRENGTHENING METALS BY SHOT PEENING

Although the art of shot peening is well developed and is in successful daily use, the science is just beginning to be understood and the theory still represents a controversial field. This is due to the complexity of the process which requires still further study and research. The reader is urged to consult the following references outlined in the Bibliography; (5)(6)(36)(38)(48)(49)(51)(52)(53). However, the various authorities are in substantial agreement on certain phases of the theory and these are presented for an aid in understanding the process.

As previously explained, the process consists of throwing numerous pellets of shot against the work to be peened with considerable velocity. Each shot which hits the work acts as a tiny peen hammer whose intensity is a function of its kinetic energy and the angle at which it hits the work. Assuming the angle of incidence to be such as to utilize a portion of the energy to do work, each shot stretches the surface of the object radially, as shown in Figure 24.

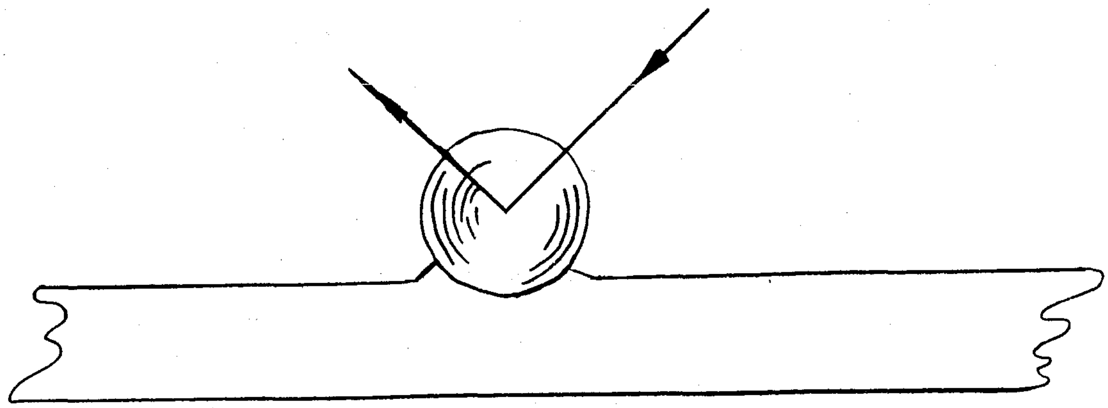


FIG. 24

This is demonstrated readily by examining the surface of the work piece, which will be found to be covered with numerous shallow dents. The dents prove that the shot has caused a plastic flow of the surface metal. The depth of cold working extends from a few thousandths of an inch for steel, to as much as 1/16" for some materials.

(5) (6) (36) (38) (48) (49) (51) (52) (53) Bibliography Pages 42, 44 and 45.

At first glance, it might seem that the denting might cause an actual decrease in the strength of the part by acting as stress raisers. However, they are very shallow and have a smooth spherical surface with a radius considerably larger than its depth. The stress-raising effect of a notch increases with its depth, but decreases with its radius, so dents made in peening, with their small depth and large radius, would cause only slight stress concentration. However, it has been shown by R. R. Moore (50) and other investigators that stress-raisers spaced close together are much less dangerous than is a solitary stress raiser. When closely spaced, they act as if they share the intensified stress among themselves, instead of leaving the whole intensification to be carried by a single stress raiser.

If the work piece is a thin sheet of steel, approximately 1/16 inch thick, it will be found to curve in the direction shown in Figure 25 after

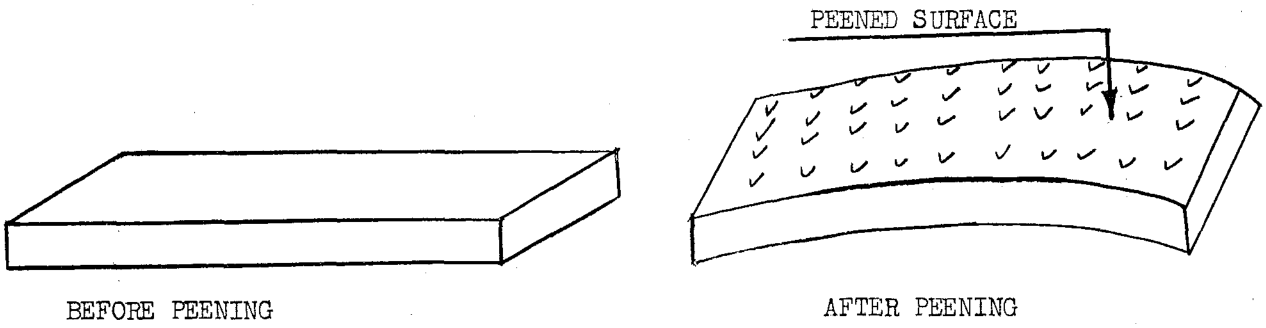


FIG. 25

shot peening (49). This demonstrates that internal forces have been introduced in the work piece by the process. If the shot peened surface is carefully removed, the strip will return to its original flat condition and this in turn demonstrates that the internal forces causing the curvature were confined to the thin surface layer.

To bend the strip in the direction indicated, the force in the shot peened layer must be compressive. As previously noted, the action of the shot is to strain the surface layer beyond its yield point and the metal below that is in its normal or elastic condition. The strained surface layer wants to occupy a greater length, but it is opposed by the elastic metal below it and hence the curvature in thin strips. In the equilibrium which results, the surface layer is in residual compression while the inner layers are in residual tension. The maximum residual tensile stress is less than the maximum residual compressive stress, except for thin pieces.

There is a wealth of evidence that the compressive stress is one of the most important factors, if not the most important factor involved in the surprising increase in fatigue strength of shot peened material.

(50) (49) Bibliography Pages 45 and 44.

DISTRIBUTION OF STRESS IN A SHOT
PEENED BEAM WITH NO EXTERNAL LOAD

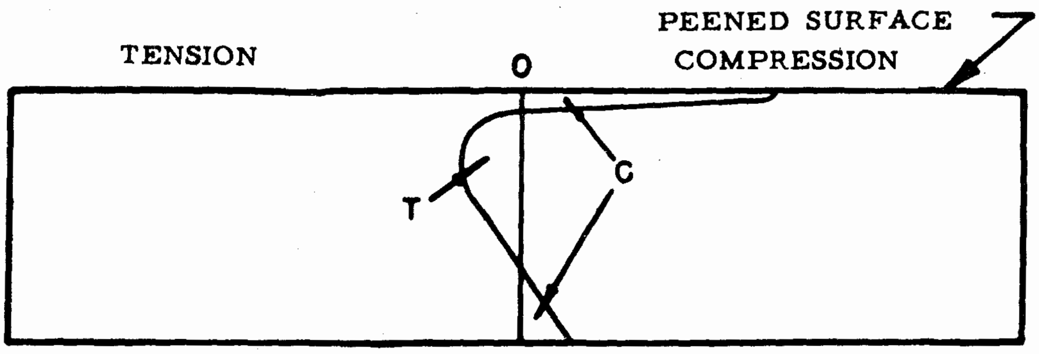


FIG. 26

RESULTANT DISTRIBUTION OF STRESS IN A
SHOT PEENED BEAM WITH EXTERNAL LOAD APPLIED.
SOLID LINE IS THE RESULTANT

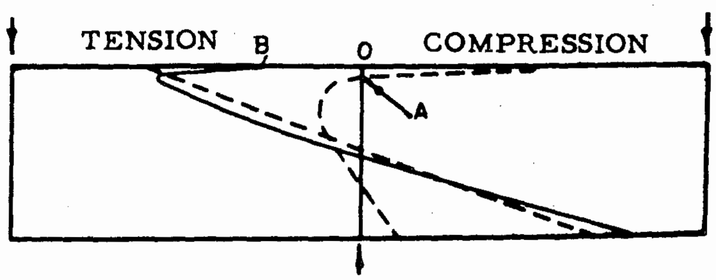


FIG. 27

The cold working of the surface layer also causes some slight increase in hardness. However, in the majority of metals used in highly stressed machine members, the increase in hardness does not appear to be sufficient to account for the marked increase in fatigue strength resulting from shot peening. For example, in spring steel, the hardness of the surface layer may be increased as much as 3 points on the Rockwell C scale. In the light of many fatigue investigations, which have shown an increase of as much as 100% in the endurance limit stress by virtue of shot peening, the moderate increase in hardness does not appear to be sufficient to explain the increased endurance limit.

In support of the theory that the increased fatigue strength of shot peened parts is due largely to residual compressive stress on the surface, tests results have shown an appreciable increase in fatigue strength even in cases where the coverage is very sparse. For example, an increase of almost 300% in fatigue life has been obtained peening laboratory specimens in such a way that only 30% of the surface was indented by the shot. This means 70% of the area exposed to the blast had not received any impact and would be subjected to little, if any, cold work. On the other hand, since the surface metal has been expanded by virtue of the impact of the shot, it would be expected that residual compressive stresses exist even in the portions of the surface which are between the indented regions.

Further evidence of the influence of residual compressive stress lies in the fact that fully hardened steel parts (60 Rockwell C and harder) have shown an increase in fatigue strength on the same order of magnitude as parts which are relatively soft. In such cases, the increase in hardness due to cold working may be considered negligible in relation to the increase in fatigue strength.

Fatigue fractures commonly start in a region of high tensile stress in a direction at right angles to it, or in a region of high shearing stress in a direction parallel to the principal shearing stress. In the latter case, after following the direction of the principal shearing stress for a short distance, the spreading fracture usually changes direction until its course is at right angles to the principal tensile stress.

The residual compressive stress in the peened surface layer increases the resistance to the start and to the spreading of a fatigue crack in at least two ways: 1) It opposes tensile stresses set up in that layer by external forces and moments, and 2) it inhibits the slipping of thin layers of the metal lying approximately in the direction of the maximum shearing stress. Greater force is required to start and to spread slipping of thin layers of metal over each other in a region under compressive stress than in a region under tensile stress. The compressive stress causes what may be called an internal friction in the metal.

Figure 26 shows qualitatively the distribution of stress in a beam which has been shot-peened on the upper surface with no external load applied. Since the beam is in equilibrium with no external forces, the area under the stress distribution curve in the regions of compressive stress must be equal to the corresponding area under the curve in the region of tensile stress. Further, the sum of the moments of these areas must be equal to zero.

Figure 27 illustrates the same beam as in Figure 26, but with an external bending moment applied, after shot peening. The resultant stress at any depth will be equal to the algebraic sum of the residual stress and the stress due to the applied load at that depth. The resultant curve of the stress distribution is shown as a solid line and the individual components are shown as dotted lines.

Note that the resultant stress on the peened surface, OB, which is subjected to tensile stress by the external load is materially reduced as compared to the stress OB in Figure 28, which is a loaded beam with no residual stresses.

DISTRIBUTION OF STRESS IN A BEAM
WITH EXTERNAL BENDING LOAD ONLY.

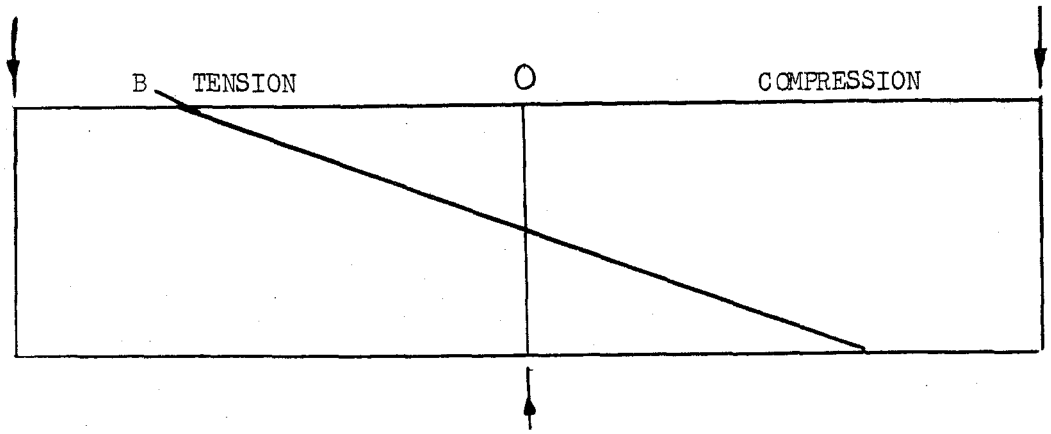


FIG. 28

The intensity of peening which is most effective in increasing the life of machine parts has been found to be influenced by the thickness or cross-section of the machine parts subject to fatigue failure. The intensity of peening depends upon the velocity of the shot, the hardness of the shot, the angle of impact and the size of the individual particle, all of which may be referred to as the potential intensity of the blast. The degree of peening is dependent also upon the time of exposure to the blast and to the number of pellets striking the work per unit area.

It has been shown experimentally that the effective part of the blast in peening is that portion which strikes the work at the maximum intensity, that is, the largest, hardest pellets striking the part at the greatest velocity and at an angle of impact nearest 90°. The limits within which the maximum is effective have not yet been defined clearly, but it appears that any pellet which strikes the work at an intensity of 20% less than the maximum is ineffective.

X-RAY DIFFRACTION OF SURFACE STRESSES INDUCED BY SHOT PEENING

Present day studies indicate that X-ray diffraction may be successfully employed in residual surface stress measurements. Direct determinations of surface stresses are possible and the results can be correlated with actual performance tests; likewise, basic research of a quantitative nature on the variables of the shot peening process are possible and yield much valuable information.

Results indicate that the outer skin develops a saturation value of compressive stress very early in the peening cycle. Increased exposure results principally in an increase of compressive stress just below the surface (in the magnitude of 0.001 inches) and a deepening of the compressive layer. Medium cycles of peening induce a compressive layer averaging about 0.008 inch deep. For example, the surface skin seems to reach a saturation value of approximately 80,000 to 90,000 psi compression for a hardness of Rockwell C45 and only increases slightly with prolonged peening. The peak stress below the surface reaches a maximum of approximately 50% greater than the surface layers. Further peening seems only to broaden or diffuse the maximum; and over-peening may be related to the movement of this peak value towards the center and a diffusion of the stress distribution.

THE EFFECT OF HEAT ON THE ENDURANCE LIMIT OF SHOT PEENED SPRINGS (38)

Recent investigations on shot peened springs indicate that heating after peening may have an injurious effect on the expected benefits derived from peening.

At room temperature, the stress range of automotive valve spring wire in the "as received" condition and not peened is 20,000 to 95,000 psi for ten million loadings with no failures. Calling the base line 95,000 psi or 100% endurance range, experience has shown that peening increases this range about 45%, so that the stress range of peened springs becomes 20,000 psi to 135,000 psi for the same test.

If springs are not heated after peening, they show more set and, while the endurance range remains the same, the top and bottom stresses are lower. When heated to 450° F. and tested at room temperature, optimum results are obtained with very little set, Figure 29. As the heating is increased after shot peening, a slight decrease is noted at 500°F., and from there to 825° F., the effect of shot peening decreases to the original stress range of 20,000 psi and 95,000 psi. Higher heating incites further reductions and lower mechanical properties all along the line.

THE EFFECT OF MECHANICAL WORK ON THE ENDURANCE LIMIT OF SHOT PEENED PARTS

Shot peening may only slightly raise the endurance limits of material which is stressed both in tension and compression, such as in reverse bending. This occurs because the stress which is mechanically induced by shot peening can be neutralized by mechanical means and therefore cannot act as a stress reducing agent for tensile stresses.

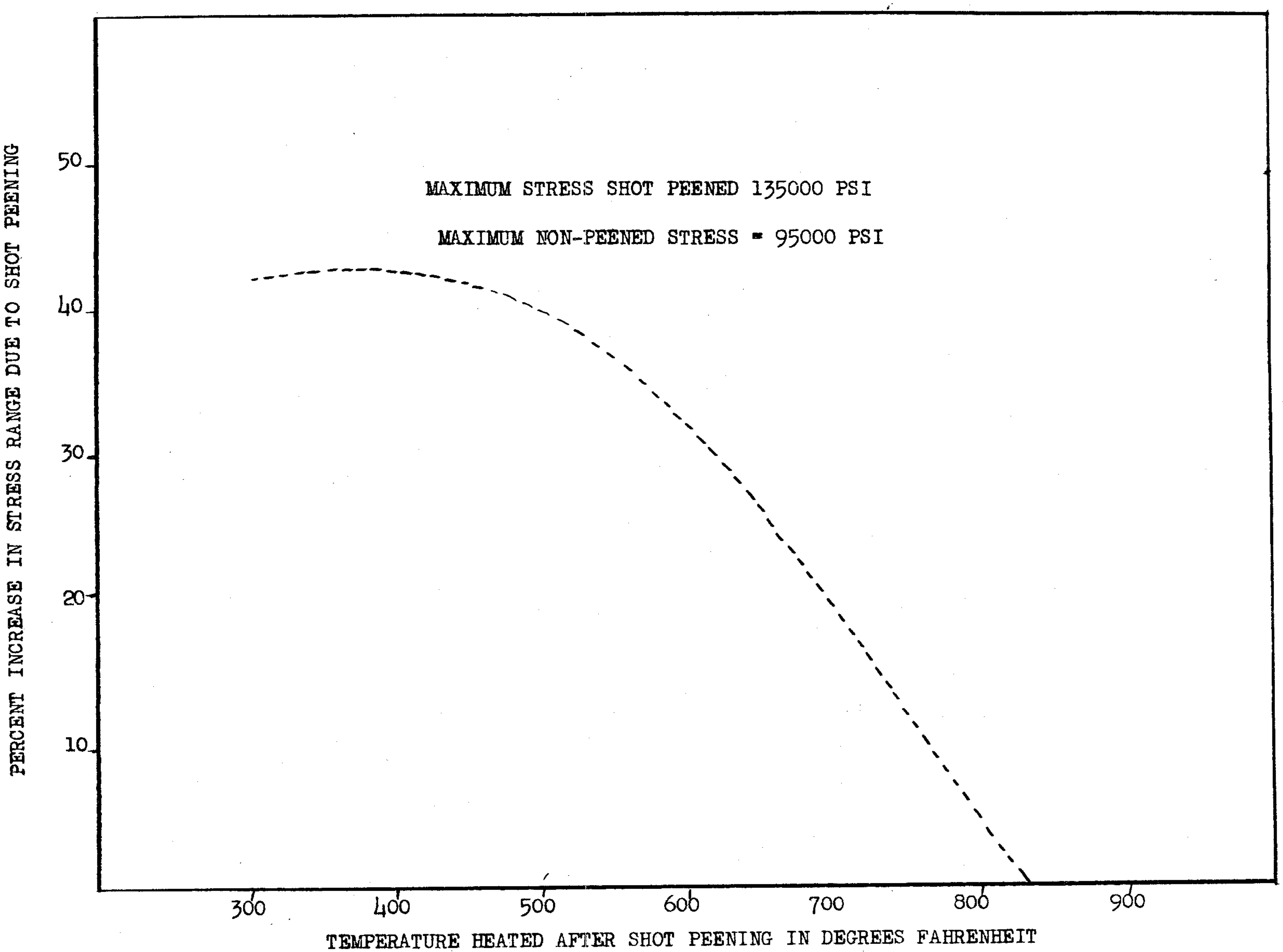
VIII. PROCESS SPECIFICATION

Shot peening is used primarily to increase fatigue strength by imposing compressive stresses in specified surface layers of metallic parts. It may have other uses, such as for bond testing of electroplates, removal of burrs and the alleviation of stress corrosion.

Peening Designation

When shot peening of parts is specified without qualification of areas, part shall be peened on all areas except small holes and cavities which are in-

(38) Bibliography Page 44.



MAXIMUM STRESS SHOT PEENED 135000 PSI
MAXIMUM NON-PEENED STRESS = 95000 PSI
PERCENT INCREASE IN STRESS RANGE DUE TO SHOT PEENING
50
40
30
20
10
300
400
500
600
700
800
900
TEMPERATURE HEATED AFTER SHOT PEENING IN DEGREES FAHRENHEIT

FIG. 29

accessible to the shot. If it is desired to limit peening to specific surfaces or areas, the portions of the part to be peened will be indicated on the drawing by arrows pointing to the surface or surfaces or by means of enclosing arrows. (A "surface" is bounded by edges of the part and/or abrupt changes in direction.)

All surfaces and areas for which peening is neither specified nor optional shall be free from indications and effects of peening. Such surfaces and areas either may be masked from the peening blast, or may be peened and the effects of peening removed by subsequent machining.

A specified peening intensity shall include a numerical value, designating the minimum arc-height, in thousandths of an inch, on a standard Almen strip peened on one side, a letter designating the type of specimen. For example, "intensity .010A" indicates a minimum arc-height of 0.010 inches on an Almen "A" specimen, as measured on an Almen Gage No. 2. If peening intensity and procedure are not specified, peening results may be specified in the form of fatigue tests, etc.

Shot size and type, time in blast, and impeller wheel speed may also be specified. However, when these and the peening intensity are specified, the performance characteristics become the sole responsibility of the specifier.

NOTE: The designation and use of types of test specimens will largely depend on the specific results desired. In general, the Almen "A" specimen is used, except for high intensities, where the arc height of the Almen "A" specimen would exceed 0.024 inches, in which case, the "C" specimen is usually used.

Material and Equipment

Peening machines shall provide means of propelling dry metallic shot by air pressure or centrifugal force against the work, and means of moving the work through the shot stream in either translation or rotation or both, as required to produce the required coverage.

Shot shall be of a material capable of producing the required peening intensity without excessive fracturing of the shot. As received, the shot shall conform to specified standards of grading (see SAE Handbook); during use, it shall be subjected to such inspection and control as will ensure that satisfactory results will be obtained. Shot used for peening parts having fillets should have a nominal diameter not greater than 50% of the minimum fillet radius to be peened.

Preparation for Peening

Parts shall be within dimensional and surface finish requirements before peening, except where peening is to be removed. All heat treatment to meet requirements for physical properties shall be completed prior to shot peening. All machining, grinding and required polishing of areas to be shot peened shall be completed, all fillets shall be properly formed, all burrs shall be removed and all sharp edges and corners to be peened shall be broken prior to shot peening.

If magnetic particle (Magnaflux) or fluorescent penetrant (Zyglo) inspection is required, parts may be subjected to such inspection either before or after peening.

The time, the shot, the shot velocity and the positioning of the parts which will produce satisfactory peening intensity on the parts shall be established by fatigue tests, and test specimens described above shall be used to control the required conditions in production peening. Specimens to be peened shall be attached to suitable blocks or fixtures or to pilot parts in such a position as best to represent production parts to be peened.

Procedure

Parts to be peened shall be suitably mounted, and masked as required, and then peened in accordance with the detail procedure established by the tests of the preceding section. Test specimens may be included with parts during peening, usually at the beginning of each production run or at suitable intervals to insure uniform machine operation. Surfaces which have been shot-peened shall have a peened or hammered appearance under macroscopic examination. Surface finish shall be uniform on all such areas of equivalent hardness. Fatigue tests should be used to control shot peening quality at regular intervals.

Post Treatments

After shot peening and removal of protecting masks, all shot and shot fragments shall be removed from surfaces of parts. Only methods which will not erode or scratch surfaces shall be used.

Light sandblasting or honing of shot-peened areas is permitted. Temperatures or stresses to which parts are subjected in subsequent processing shall not be high enough to reduce stresses imposed by shot peening or to affect the physical properties of the material adversely.

Tolerances

Unless otherwise specified, variation from specified peening intensity shall be -0 to + 5 (-0.000 to + 0.005 in. arc height on test specimens).

Unless otherwise specified, the variation in boundaries of areas to be peened, when limited, shall be -0 to + 1/8 inch.

IX. EXAMPLES OF TYPICAL METHODS IN CURRENT USE

METHODS OF SHOT PEENING SPRINGS

TYPE SPRING (Hot Coil)	Mfr. A	Mfr. B	Mfr. C	Mfr. D	Mfr. E	Mfr. F
		A U T O M O	T I V E	P A S S	E N G E R	
Spring Size						
Steel Size (Bar diameter)		.54-.80		.568	.725	.592"
Steel Hardness		415-512	444-461	Rc 51	Rc 51	387-477
I. MACHINE USED						
A. WHEEL TYPE						
1. No. of wheels	2	2	2	2	2	2
2. Width wheels (ins.)	1-5/8"	2-1/2"	5"	1-5/8"	1-5/8"	1-5/8"
3. Dia. wheels (ins.)	19-1/2"	19-1/2"	19-1/2"	19-1/2"	19-1/2"	19-1/2"
4. Wheel speed (rpm)	2250	2000	2250	2000	1800	1800
5. Total lbs. shot thrown per min.	-	267#	-	145#	300#	332#/w
6. Barrel or conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.
B. CONVEYOR TYPE						
1. Speed conv. (lin. ft. per min.)	14.3'/M	15'	12'	17-1/7'	17-1/7'	15'
2. Workrotated-(rpm)	100	60	60	54	54	65
3. Distance of nozzle or rim of wheel from top of work (ins.)	16"	15"	-	15"	15"	16"
II. SHOT						
1. Kind of shot used*	CI	CI	CWS	CI	Cut Wire	Cut Wire
2. Size shot bought	#170	P23 & 28[1]	P28[1]	230 & 330	.035"	.035"
3. Avg. size of shot in machine, 85% on	.014"	.012"	.035"	-	.033"	.033"
III. MACHINE CONTROL						
1. Almen reading range A	.011/.015	013/.017	.015/.019	Avg. 013	012-.016	.016-.020
2. Type of fixture for holding strip	I.D.Spg.	I.D.	-	I.D.Spg.	I.D.Spg.	I.D.Spg.
3. Other test	-	Valentine	B/17	Faxfilm	Faxfilm	Faxfilm

*CI - Cast Iron
CWS - Cut Wire Shot
CS - Cast Steel

Note 1 - Shot sizes are given in old Standard. See 1951 SAE Handbook.

METHODS OF SHOT PEENING WIRE COIL SPRINGS

TYPE SPRING	Manufacturer G			Manufacturer C		Mfr. B
Spring Size Steel Size (Wire diameter) Steel Hardness	Small pitch (bel. .105)	(others)	1/4"-1/2"	Valve	Misc.	Valve .162 Rc 45
I. MACHINE USED						
A. WHEEL TYPE						
1. No. of wheels	1	1	1	1	1	1
2. Width wheels (ins)	-	-	-	2-1/2"	2-1/2"	2-1/2"
3. Dia. wheels (ins)	15"	15"	15"	15"	15"	19-1/2"
4. Wheel speed (rpm)	2300	2300	2300	2250	2250	2000
5. Total lbs. shot thrown per min.	300#	300#	300#			225#
6. Barrel or conv.	Bbl.	Bbl.	Bbl.	Bbl.	Bbl.	Conv.
B. BARREL STYLE						
1. Quan. springs per load (lbs. or pcs.)	½ Full	½ Full	½ Full			
2. Time in bbl (mins.)	20-60	20-60	20-60	10	10	
3. Distance of nozzle or rim of wheel from top of work	23 to 25"	23 to 25"	23 to 25"			
C. CONVEYOR TYPE						
1. Speed conv. (lin. ft./min.)						11/13.5
2. Work rotated — (rpm)						rolled
3. Distance of nozzle or rim of wheel from top of work						21"
II. SHOT						
1. Kind of shot used *	CI	& CS		CS	CS	CI
2. Size shot bought[1]	P16	P28	P46	P28	P28	P23 and 28
3. Av. size of shot in machine, 85% on screen						.012
III. MACHINE CONTROL						
1. Almen reading range A	.006/7	.012/14	.016/20	.008/1010	.008/.010	.006/.012
2. Type of fixture for holding strip	Almen Block with load					I.D. Spg.
3. Other test						Valentine

* CI - Cast Iron
CS - Cast Steel

Note 1 - Old Standard used for sizes. See 1951 SAE Handbook.

METHODS OF SHOT PEENING AUTOMOTIVE LEAF SPRINGS

TYPE SPRING	Manufacturer C	Manufacturer B
Spring Size (width in inches)		to 2"
Thickness in inches		.30
Steel Hardness - Brinell	418-444	Av. 444
I. MACHINE USED		
A. WHEEL TYPE		
1. No. of wheels	1	1
2. Width wheels (ins.)	5"	5"
3. Diameter wheels (ins.)	19-1/2"	19-1/2"
4. Wheel speed (rpm)	2250	2200
5. Total lbs. shot thrown per min.		500
6. Barrel or conveyor	Conveyor	Conveyor
B. CONVEYOR TYPE		
1. Speed conveyor (lin. ft./min.)	27-1/2'	28'
2. Work rotated-- (rpm)	No	No
3. Distance of nozzle or rim of wheel from top of work (ins.)		21"
II. SHOT		
1. Kind of shot used *	CI	CI
2. Size shot bought[1]	P28	230
3. Av. size of shot in machine, 85% av.		.012/.018
III. MACHINE CONTROL		
1. Almen reading range A	.012 ± .002	.009 - .020
2. Type of fixture for holding strip		--on leaf
3. Other test		--arc rise of work

* CI - Cast iron

Note 1 - Old Standard used for sizes. See 1951 SAE Handbook.

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