HOW SHOT PEENING MAKES BETTER GEARS

BY

PHILIP E. CARY

Consultant to
METAL FINISHING SERVICE
Chicago, Illinois

AND

ROBERT E. WAHLSTROM

Research Associate Metallurgist
INTERNATIONAL HARVESTER CO.
Hinsdale, Illinois

1973007

Presented before the Vehicle Gearing Committee
and the Aerospace Gearing Committee,

AMERICAN GEAR MANUFACTUERERS ASSOCIATION
at
New Orleans, La.

November 6, 1973

HOW SHOT PEENING MAKES BETTER GEARS

By

Philip E. Cary and Robert E. Wahlstrom

A talk before The American Gear Manufacturers Association
Vehicle Gearing Committee and Aerospace Gearing Committee
meeting at New Orleans, La., November 6, 1973

(Note: The authors have prepared this informal)
(presentation for use within A.G.M.A. It is not)
(for publication or general circulation.)

Peening is an old technique. It probably became a specific skill when the earliest metal-workers found that metal that was heated and shaped, or forge-welded in the hot, plastic stage, would contract upon cooling and try to separate from the larger body of the part. This would cause tensile stresses, often leading to cracks. They reasoned, correctly, that if they expanded the tensioned area by hammering, they could relieve the tension and avoid the cracking.

Today, we carry this reasoning one step further. We hammer the surface of the finished part even more, with round steel shot, and produce higher compressive stresses in the surface. This makes the part capable of withstanding considerable bending before the surface goes into tension,(which might lead to fracture).

Figure 1. will illustrate this point.

HISTORY

In 1927 E.G. Herbert[2], in Levenshulme, England, produced and sold what is believed to be the first machine for peening in quantity, under controlled conditions. He called it the "Cloudburst Machine". It was designed to drop quantities of hard steel balls from an adjustable height, so they would strike with uniform spacing and impact on the work-piece. Figure 2. is an illustration of the machine, and Figure 3. shows the result of the 'cloudburst' on a steel disc which had non-uniform hardness. Notice that the soft areas were deeply indented, while the hard areas were scarcely marked.

Mr. Herbert was not looking for a shot peening machine at the time he developed the cloudburst apparatus. He had, about 4 years before, introduced his "Herbert Pendulum Hardness Tester", shown in Figure 4. It operated by causing a hard steel, or diamond, ball to roll on the surface of the work-piece under heavy load, as depicted in Figure 5.

The period-time of the Herbert pendulum was found to be different as the ball rolled on hard metal, compared to soft. The length of swing of the pendulum was also found to change. But in analyzing the cause of these changes in timing, Herbert observed that when the ball retraced its path in the groove produced by its first swing, the time-period changed, and became less and less - up to a point. He had discovered a simple way to measure the work-hardening ability of metal as a by-product of measuring so-called "hardness".

Other hardness testers were being developed at about this time. Brinell, 23 years earlier, had introduced his hydraulically loaded ball impression machine.

Examination of hardness tests leads us to the point that the forces required to indent, or displace metal are related to the term called "hardness". We may say, conversely, that the hardness of a metal bears a relationship to the mechanics of displacement of metal during an indentation.

The Appendix I., to this paper expands upon the history of the development of hardness tests.

In about 1929 Mr. F. P. Zimmerli put shot peening to work increasing the strength of springs. J. O. Almen, R. L. Mattson, and J. C. Straub of General Motors and H. F. Moore of Wheelabrator Corp. and many others contributed to the early development of the process.

THE MECHANICS OF PEENING

We must keep in mind that some metals, as Herbert found out with his pendulum tester, work-harden, or cold-work, to a much greater degree than others in the process of indentation, as shown in Table I, and Figure 6.

TABLE I.

TYPICAL WORK HARDENING NUMBERS

Material	1st.	2nd.	3rd.	4th.	5th.	Av. of Last Four	Work Hardening Capacity
Hard tool steel	83	92	95	94	96	94.3	11.3
Manganese steel	14	83	78	95	80	84	70
Stainless steel	18	71	66	79	76	73	55
Mild steel	15	52	48	55	45	50	35

(Herbert "Scale" Work-hardening Numbers)
Increased hardness due to 5 passes of the Herbert Pendulum ball over the same imprint.

(Ref. 1.)

Herbert was attracted to this challenging observation, and he pursued it using his Cloudburst machine. In a paper entitled "The Work Hardening of Steel by Abrasion", which he presented before the Iron and Steel Institute, in Glasgow, in 1927[1], Herbert described his studies of "superhardening" by peening. Among his several observations he brought out one very interesting point often overlooked:

> "An article placed in such an atmosphere (quantities of small hard steel balls traveling at high velocity)* -- would be subject to a rapid succession of blows, and if a certain relationship existed between its hardness and the atmospheric* pressure, i.e., the momentum of the balls, its surface would be compressed without being sensibly indented. The article,

> if of hard steel, would become encased in a thin super-hardened layer. If the velocity of the balls were now slightly increased, the hard layer would resist indentation, but would be increased in hardness, and in thickness. By gradually increasing the velocity of the balls, a super-hardened layer could be produced, intensely hard on the surface and gradually decreasing in hardness throughout its thickness, which might be about 2 mm."

Today we have verified that it is not necessary to make deep impressions in the surface of a part in order to produce the desire compressive stresses. In fact, maximum peening is often accomplished without any visable marking. Valentine's microscopic grain growth test for cold-working, as shown in Figure 7, X-ray diffraction tests, and direct fatigue testing of finished parts are reliable tools for confirming the acceptability of the shot peening process.

Now, after shot peening and testing for many years, we can say that the ability of shot peening to improve the strength of a structure is dependent, (1), on the metallurgical characteristics i.e., the case depth, hardness, heat treatment of the material being peened, and (2), the work-hardening ability of the material being peened, and (3), on the characteristics of the shot blast, the velocity, size, and hardness of the shot, and the obliquity of its impact.

(A.) WORK-HARDENING ABILITY OF THE PART MATERIAL

Figure 7 is a good illustration of how the work-hardened zone extends a considerable distance out beyond the actual impression.

Identification of the work-hardened depth is made possible with K.B. Valentine's method of recrystallization, which is described in the section under "Control of the Peening Process". Work-hardening as shown by recrystalized large grains, extends beyond the edge of the crater to a distance equal to about 1/3 of the diameter of the impression. Thus one may see that a very useful continuous layer of work-hardened metal can be produced without 100% coverage of the surface by indentation marks, if all details of the peening are carried out under close control.

It is also clear that when the part material is very hard, the impressions of the shot will be smaller, and more impressions may be needed to produce a complete bridge of worked metal between them. If the metal is readily work-hardened a lesser coverage can be tolerated. Knowledge of the metallurgical response to be expected from the material in the part is vital to success of the process.

Table III lists changes in physical properties when several steels are work-hardened, (cold-reduced).

TABLE III WORK HARDENABILITY OF STEEL

Steel Grade	Condition	Work Hardened Condition, %.R.A.	1000 psi Tensile Str.	1000 psi Yield Str.	1000 psi Fatigue Str.	BHN Hardness
1016	Annealed	-	60	41	28	126
	Work-hardened	20	87	85	43	178
1019	Annealed	-	71	51	35	147
	Work-hardened	12	84	72	42	169
1029	Annealed	-	72	-	35	-
	Work-hardened	36	104	78	45	210
1037	Annealed	-	72	35	33	-
	Work-hardened	90	226	-	65	400
1045	Annealed	-	93	69	47	190
	Work-hardened	6	108	84	55	213
1055	Annealed	-	-	-	-	-
	Work-hardened	90	274	-	75	535
4140	Annealed	-	89	62	45	187
	Work-hardened	6	102	90	51	223

(ref.#3)

(b.) THE ACTION OF THE PENETRATOR

Figure 8 illustrates how a pointed plow passes through a snow-drift. The point, at (2) must cleave between, or through the crystals, then the mass of snow is pushed to either side at (3) with resistance to be overcome in distorting the adjacent snow field, at the same time the moving wedge is required to overcome the sliding friction of snow on its surfaces.

Similar action takes place when a conical penetrator enters a metallic body, as shown in Figures 9 and 10.

The contour lines in the lower portion of the figures represent bands of equal hardness in the sectioned view after the penetration, caused by work hardening; while the upper portion describes the hardness across the exposed surface of the part. Notice that with the 60° penetrator in Figure 9, the maximum hardness was obtained on the inner surface of the crater. While with the 120° penetrator, in Figure 10, the maximum hardness was produced at the apex of the crater, where it becomes a most undesirable stress-raiser.

Now observe that a ball penetrator, as in Figure 11, produces the maximum work-hardening below the surface of the part, and it is quite well distributed laterally. This is a good example of why spherically shaped particles are preferred in shot peening, rather than broken, angular particles. A spherical body impacting a flat surface will tend to distort as shown in Figure 12. Some energy is lost as heat, in distorting the sphere, and at the same time the remaining energy of the ball is distributed over a wider contact surface, transmitting lower unit loading of the flat surface. Thus the peening action is less effective, and the sphere is subjected to severe stresses that cause shorter life, if not immediate fracture. It is better to use a ball at least as hard as the work-piece if most effective work-hardening of the part is the purpose. On the other hand, a softer shot can often be used at lower velocity, when less than maximum peening effect is acceptable. This is an important economic factor where large volume peening is being done.

When the shot penetrates hard material the supporting metal around the crater resists flow and forces the displaced material to raise up to form a "ridge", as shown in Figure 13. If the work-piece is soft and malleable, however, the displaced metal is driven into the part and causes a flow of metal out some distance away from the crater, to produce the "sinking" type crater shown in Figure 14. Here again, the material of the work-piece is responsible for variations in the final product and roughness, of the peening process.

We have discussed some differences in depth of the work-hardened layer due to shot size and coverage, but Figure 15 shows how hardness of the part is important in the relationship of actual depth of the affected layer to the corresponding "intensity" of the blast as measured by the Almen gage. The harder the part being peened, the less the depth of worked metal, when exposed to the same blast intensity.

Figure 16 is a graphic illustration of how the layer of affected metal in the work may be complete (and of adequate depth for many purposes) without going to the expense of complete coverage. Use of this approach requires close control of the peening process, however.

CONTROL OF THE PEENING PROCESS

S.A.E. specification J-444 sets out the recommended limits for different sizes of shot for peening. It permits more large shot in the mix for a given shot class than does the latest military specification MIL-S-13165B. This makes it impossible to obtain quite the same maximum peening intensities with the MIL spec.

Either specification is usually intended to describe the size limits for new shot. After the shot is in use it breaks down at a rapid rate and requires constant examination and additions of new large shot to maintain constant peening intensities and quality. If the fines and broken particles are pemitted to recirculate in the peening machine the visual appearance will indicate surface impacts, as shown in Figure 18, where grit was used.

The peening effect, as we have already pointed out, will not be equal to that produced with closely sized round shot, as shown in Figure 17. Both would be rated as about 96 to 100% coverage. Casual visual examination may indicate no difference, but when examined under a glass the sharp marks of broken shot and fines can usually be distinguished from the spherical impressions desired in proper peening.

Figure 19 shows limited data on the effect of shot size on Intensity and on Fatigue Life achieved. While higher intensities can be obtained with large shot, maximum fatigue life for a given steel and use of the part can often be obtained by S230, or even S170 shot in practice, and at less cost.

The Almen gage, shown in Figure 20, is the only acceptable way at this date, to measure and identify the intensity (force) of the blast. The gage can be used two ways: (1) by placing it a standard distance from the blast stream source, and normal, (90°), to the trajectory; or (2) by inserting the gage into a simulated work piece so the test strip surface represents the most critical area to be peened.

When the latter method is properly used it measures the actual blast effect, including shading of the critical areas and taking into account various angles of impact associated with the blast. But this is often expensive and even impossible in some small parts, since the gage is 3 inches long. So it is necessary sometimes to measure the blast stream and see that it is reproducing, and then apply the 'calibrated' blast to the part and describe the positions, distances etc. The part is then physically tested to see if it meets performance requirements, and if it does, the peening set-up is completely recorded for future re-runs.

Figure 21 shows the gage inserted in a dummy crankshaft according to method (2).

"Coverage" of the surface of the part with impacts may be measured according to methods recommended in Reference (9) or (11), or may simply be reported as "Percent visual coverage", by estimate, if the process is not under tight control. Economics of the treatment and critical nature of the part in use will dictate the degree of precision and control needed in the process. Figures 22 and 23 represent 45% coverage and 94% coverage.

respectively. A curve showing the theoretical relationship between exposure time and "coverage" is given in Figure 24.

The angle of impact of the blast stream and the surface of the work can have important influence upon the actual intensity effective on the part, as shown in Figure 25. Figure 26 is representative of the difficulty in getting the blast to impact on all surfaces equally. This situation also occurs when peening gear teeth, so that it may be necessary to direct the blast from two or more positions. Usually, however, adequate peening can be obtained by directing one blast stream into the gear tooth root fillet since this is the area of more severe concentration of bending stresses.

Determination of the "hot spot" of the wheel or air gun blast is part of the procedure in control of the process.

One word of caution: the Almen intensity gage strip is a meaningful measure only if the entire surface is treated uniformly with the blast effect. Local spot blasting of the strip can lead to faulty control.

When parts are placed in the blast stream, it must be done with concern for repeatability and ability to meet quality requirements, but often the economics of the process are unacceptable because of poor fixturing and planning. Areas that require masking from the blast stream may become the most costly part of the proceedure. There are many ingenious ways of masking that can reduce cost however. To evaluate the entire peening application on a given part we have 3 choices:

(1) Use Almen gage to establish intensity of the blast at a standard distance from the blast source. The gage is not mounted in the part. Peen typical production parts to selected intensities etc., and then

fatigue them in a manner paralleling service use to determine the adequacy of peening. Duplicate all future set-ups from detailed records made of these pilot tests and keep blast stream intensity within limits used in original tests.

(2) Make a fixture or simulated work-piece to receive one or more Almen gages in the most critical areas. Vary the air pressure or wheel speed, shot size, gun angle and distance, etc., until the critical areas are exposed to the desired treatment. Record all settings and use this and the gage readings as the specification for future set-ups.

(3) Make a simulated part from plain low carbon steel. Experiment to obtain desired blast in all critical areas. Anneal the part at about 1300°F for 2 hours or more to promote grain growth. Section and examine work-hardened areas under the microscope. Readjust the peening proceedure until satisfactory depth etc. is obtained. Record all settings for future set-ups.

MACHINES USED IN PEENING

Herbert used gravity to give the shot the velocity he felt was needed for his experiments in peening. Pangborn and the Wheelabrator Corporation (now Wheelabrator-Frye) adapted the wheel to a machine for throwing shot. Many people have sold air gun equipment, both the inductor nozzle type and the direct pressure type. All will do good shot peening. The shape of the blast is peculiar to each method.

The wheel machine principal is shown in Figure 28 and the construction of the induction nozzle in Figure 29. Costs of operation are discussed in a later section, it is suggested that a user get in touch with the various manufacturers for details of each. Air guns of course, will be more suitable for peening in limited access situations. The direct pressure type gun can produce higher intensities than the induction gun, which is limited to about .015A2. The direct pressure gun can also deliver shot at a higher flow rate than the induction gun.

A wheel machine can deliver very large quantities of shot per minute, however it is less flexible to position than the air guns. Usually the wheel moves a great deal of shot which never contacts the work, so for some kinds of use it may be less suitable, altho potentially more efficient than air guns.

RESULTS

Figures 30, 31, and 32 illustrate some variations in the depth of compressed metal that can occur. Notice the inadequate depth in Figure 31 which has only 45% coverage; the others had 100% and 94%.

Figure 33 describes Almen and Black's[12] placement of S-N fatigue curves for cyanided, carburized, and carburized shot peened gears. The improvement caused by shot peening is apparent, but derivation of the curves is not clear to these authors.

Figure 34 depicts S-N curves prepared by H. F. Moore[9], which clearly show the improvement through shot peening two different steels.

Note again the importance of the steel in the part, in securing the maximum benefits from peening.

Almen and Black[12] have a very good illustration of the chipping that can occur when thin-cased parts are over-peened.

Halgren and Wulpi,[15] found typical improvements in fatigue strength of gears by shot peening:

<u>CASE 1.</u> <u>SMALL, 23 TOOTH PLANET GEARS</u>, about 8 pitch 4118 steel, machined, carburized to .025"-.035" depth, marquenched in 400°F oil for 10 min., air cooled and tempered to $60R_c$.

Single tooth one-direction bending fatigue test:

NOT SHOT PEENED	SHOT PEENED
endurance limit = 2350 lbs (4 gears)	3025 lbs. (4 gears)

<u>CASE 2.</u> <u>SAME</u>, Made from 4817 steel.

NOT SHOT PEENED	SHOT PEENED
3550 lbs. (2 gears)	4900 lbs (1 gear)

<u>CASE 3.</u> <u>24 TOOTH SLIDING TRANSMISSION GEARS</u>, 4.8 D.P. 1.4" tooth width, 25° P.A. TS-8620 steel, machined, carburized, quenched in oil and tempered.

NOT SHOT PEENED	SHOT PEENED
12,500 lbs (4 gears)	15,250 lbs. (4 gears)

<u>CASE 4.</u> <u>77 TOOTH SPROCKET DRIVE GEARS</u> 31" O. D., 4" W., 22° P.A., 2.5 D.P. 1045 steel roll-forged, normalized, machined, and induction hardened.

<u>CYCLES</u>, (at tangential load of 84,800 lb), to failure:

NOT SHOT PEENED	SHOT PEENED
35,000 to 88,000 cy.	89,000 to 715,000 cy.
(16 tests, 4 gears)	(13 tests, 4 gears)
av. 62,900 cy.	av. 218,500 cy.

It has been well established that reverse bending will severely reduce the life of parts operating near the endurance limit, compared to simple bending. Comparisons by accelerated laboratory tests should take this into account and gear designers should be prepared to deal with this fact. Peening gears which are subject to drastic reverse bending may sometimes, even reduce the apparent strength of the part.

COSTS OF PEENING

Appendix II provides a helpful comparison of the power required for peening with a wheel,induction gun, or direct pressure guns. These figures are based on continuous operation on repetetive parts. Installation and capital costs are not included, and are an important factor.

Table II lists typical costs to shot peen carburized gears, based on full loads, continuous operation, no allowance for changing set-ups. The prices must be adjusted, of course, to present-day conditions.

CONCLUSIONS.

In summary, then, we would like to re-emphasize these points:

Mechanical treatments such as shot peening of high strength parts should be given the same metallurgical consideration as heat treatment. Materials which are highly responsive to work hardening offer great opportunity for improvement of fatigue strength by shot peening, while other materials offer less. Exposure to temperatures higher than the tempering temperature for the part will reduce the benefits that may have been put in by shot peening.

Parts that are exposed to reverse bending often may not show as much benefit from shot peening as parts having single-direction application of load.

It is possible to over-peen, depending on the metallurgical structure and the geometric shape of the part, and its use.

In the interest of economy and conservation of energy, do not apply mechanical treatments except where needed, but, on the other hand, weigh the advantages and costs, and consider this treatment as a means for reducing weight and size of the part while increasing its strength and performance.

Philip E. Cary

Robert E. Wahlstrom

November 6, 1973

Appendix I

ON PENETRATION OF METAL BY AN INDENTOR

Probably the earliest efforts to evaluate the hardness of metals consisted of scratching the unknown material with something of familiar hardness, such as glass, diamond, or some common metal. Later, in 1722, Réaumur pressed right angled prisms of known character, into similar prisms of the unknown material, and secured a comparison of hardness. A few years later, in 1729-1756, P. Musschenbroeck used a knife which was struck with a particular ivory ball. The number of blows needed to cut through the material was divided by its specific gravity as a measure of the hardness of the material.

Between 1822 and 1884, F. Mohs and others expounded on the "scratch method" of measuring hardness.

About 1856 a Commission of American Artillery Officers experimented with methods for measuring the strength of metals used in cannon. They determined hardness using a pyramidal cone and a weight of 10,000 pounds to make an indentation, and then measured the volume of the cavity. From 1875 to 1891 several investigators, (including the classical efforts of H. Hertz and F. Auerbach), experimented with various forms of static penetration tests for hardness. In particular, in 1900, Dr. John August Brinell, then Chief Engineer of Fagersta Iron and Steel Works in Sweden, proposed a static indentation method using a steel ball, and measuring the diameter of the impression. The Brinell test has survived to the present. The Rockwell type penetrator is an offshoot of the Brinell approach, using a different method for measuring the result. Other static penetration tests use pyramidal-shaped penetrators, and some work has been done with conical, truncated cone, and even flat-tipped cylindrical penetrators.

---

(1), (2), (4), and (5) refer to Bibliography of main paper, "How Shot Peening Makes Better Gears", Nov. 1973.

A mathematical analysis of ball penetration has been presented by several authors, but Professor Eugene Meyer, of the Imperial School of Technology, Charlottenburg, Germany, in 1908, established constants which are the basis for todays approach to penetration tests.

It is interesting, with regard to shot peening, to note that P. Ludwik[4], in Germany in 1908, investigated 90° conical penetrators in relation to spherical penetrators, and this relationship has been re-examined and reported by R. P. Devries in National Bureau of Standards Technological Paper No. 11. The relationship of conical indentors to ball indentors can be of assistance in evaluating the merits of round shot compared to angular shot in peening.

Of major importance in the analysis of peening methods, however, are the theories underlying dynamic penetration tests, and their relation to material characteristics.

Lieutenant Colonel R. Martel, in France in 1895, studied dynamic hardness testing. He reported that "the volume of indentation produced by a falling hammer is proportional to the height of the fall, and the mass of the hammer, and <u>independent</u>* of it's (the indentor's) shape. Martel's statement "-- applies to malleable materials which can have their molecules displaced without rupture".

This discovery of Martel's, and related theoretical analysis by Kokado, Schneider, Baker and Russell, Edwards and Willis, and Batson, have enabled reliable measures of hardness to be made dynamically, if one exercises due concern for the influence of the work-hardening characteristics of the material. In other words, the ease of penetration can be either a measure of inherent "hardness", or can be a measure of work-hardening ability of the material, or a combination of both.

(*) Later, C. A. Edwards, in England in 1918, (and verified by S. Kokado, in Japan in 1927) determined that as the ball diameter or the cone angle increased, there is a slight deviation from Martel's statement. They provide the precise mathematical analysis of dynamic penetration that is used today.

In 1906, in the United States, A. F. Shore introduced the Schore Scleroscope Model C-1, a dynamic hardness tester using a falling hammer. It employed a "Universal" hammer, or 'tup', made of mild steel, 0.240 inches in diameter weighing 2.5 grams and having a specially shaped diamond tip or indentor. The hammer was allowed to fall from a constant height of 25 cm, and the height of rebound was observed. For soft metals a blunt steel conical-shaped Magnifier hammer was used. This could be replaced by a Magnifier hammer using a 3mm steel ball indentor if desired. By repeated tests with the scleroscope on the same spot, an indication of the work-hardening character of the material could be obtained. Repeated impacts showed increasing rebound as work-hardening progressed. After 6 to 10 impacts a maximum rebound was usually obtained. Subsequent impacts would show slightly lesser rebound height.

In 1928 Monsieur P. Roudie, a French engineer, built a hardness testing machine called a Sclerographe, which was a dynamic type having a falling hammer similar to Shore's but weighing 50 grams. It embodied a 5mm ball indentor. The normal fall was 100mm and rebound was measured. For soft materials the face of the 5mm steel ball was reground to a diameter of curvature of 100mm. For hard steels a 130° cone indentor of work-hardened, quenched steel was available for greater sensitivity. There were other designs of rebound testers. Roudie presented a very thorough analysis of dynamic hardness testing.

O'Neill[5] points out that"The behaviour of a metal as regards deformation is appreciably affected by <u>large</u> alterations in the speed at which the deformation is effected".

E, G. Herbert[2] of Levenshulme, England, introduced a novel instrument in 1923. It was shaped like an inverted "U" and weighed a total of 4 kilograms. It incorporated a support for a 1mm hard steel, (or diamond), ball at the inner center of the arch of the "U". The center of gravity of the device was set to be 0.1 mm displaced from the surface of the ball towards the legs of the "U", so that the whole thing would act as a pendulum about the ball. A bubble inclinometer was set into the arch of the "U", calibrated 0 to 100, with "50" at the center of the pendulum. This enabled one to make a "Scale Hardness" test by tipping the pendulum, while it rested on a test piece, to register "0" at one end of the curved inclinometer scale, then releasing the pendulum. On a very hard material, such as glass, the pendulum would swing, rolling on the ball indentor, until the bubble would nearly reach the other extreme of the scale, "100", before starting its return. When a soft material, such as annealed carbon steel was tested, the bubble would travel only to about "40" on the scale. This was called the Scale test, or "S" hardness.

Another test could be made with the device by observing the total time required for the pendulum to achieve 10 half cycles, (5 complete cycles). This was called the Time test, or "T" hardness.

The pendulum tester could also be used to measure the work-hardening ability of a material by oscillating it a selected number of times in the same impression, and noting the amount of increase in Scale hardness, or Time hardness, in that impression.

W. D. Kusnezow, in about 1931, invented a pendulum tester that had two indentors, both either hard steel points, or hard steel balls, positioned at the fulcrum as a knife edge might be. The center of gravity was a greater distance below the indentor than in Herbert's pendulum. The total weight varied from 374 grams, for testing graphite, to 1023 grams for $CaSO_4 2H_2O$ crystal, to 5000 grams for testing glass. P. Rehbinder, very shortly after Kusnezow, successfully used this pendulum to detect the relative effect of paraffin oil vs paraffin oil plus oleic acid, as a lubricant on the penetrators.

Mr. A. Hultgren[4], in 1924 in Sweden, provided Brinell with an added improvement to his testing of hard metals, (675 - 700 BHN), by making hardened - cold worked[1,5] steel balls in 5 mm and 10 mm sizes. Hultgren probably performed one of the first controlled cold-working operations by rolling these balls while overloading them in a specially designed raceway. British Specification No. 240, Part 2, 1929, requires these balls to be not less than 900 DPN, (67 R_c).

About this same time gear wheels[5, p129] were also being produced in the United States whose teeth were specially burnished and "superhardened" by finishing the blanks against hardened and ground master gears.

Probably the most important link between penetration hardness tests and shot peening occured in 1927 through the efforts of E. G. Herbert, just a few years after he invented his pendulum hardness tester. In order to more readily detect soft areas in a hardened part he conceived the idea of dropping quantities of 3mm or 5mm hard steel balls from a selected height, (usually 2 to 4 meters), that would not indent a properly hardened part, but would visably indent any area that was softer than desired. He called this the "Cloudburst Test" for hardness[2]. By dropping only a few balls, their separate indentations could be measured, if desired, using a microscope, and thus actual hardness values could be obtained. He could easily differentiate between acceptable and unacceptable areas.

A properly hardened but undesirably thin, (less than .5mm) carburized case could be identified because the case would crack or break in the cloudburst test.

Herbert found, in the process of studying his cloudburst test, that a very considerable increase in hardness was obtained on the surface of a part, (to a depth of 0.6 to 2.0mm), that had been exposed to the Cloudburst procedure.An outstanding case was 14% Mn. steel, which was raised from an initial diamond pendulum "Scale" hardness number of 14 to 84, (or a Time hardness number of 27.6 to 64.0). This hardening process was given the name of "Superhardening".

Appendix II

From R.B. Huyett, Panghorn Corp., "Shot Peening Increases Life of Machinery Parts." (Steel Processing. October 1947, P609-613-638 &647.)

WHEEL - Shot velocity is determined by peripheral speed of wheel. Normal wheel diameter and RPM produces velocity of shot about equal to a direct pressure gun at 80psi.

Normal Volume of shot from a wheel is about 10 times the volume handled by a 3/8" direct pressure gun at 80psi, and power consumption is about 1/10 that of a compressor to drive the gun. (But since the delivery of shot from the wheel is not closely concentrated, as in a gun blast, the usable volume handled may be only 8 times that of an air gun and the power consumed only 1/8 that of an air gun.)

A wheel, using a 20 HP motor, handling 400 lbs of shot per minute in about equal to 10 - 3/8" direct pressure nozzles operating at 80psi, requiring 1900 CFM and 200 HP.

INDUCTION GUN

The air jet is usually about 1/2 the diameter of the main nozzle opening. The shot volume handled in this gun is about equal to the shot volume that would be handled in a "direct pressure" gun of the same size as the induction gun air jet.

The velocity of the jet stream is retarded somewhat by the energy used in creating the partial vacuum for induction of the shot. Therefore, peening intensities are usually limited to about .016A2. The shot is metered thru a separate orfice.

A typical induction gun with 7/32" jet could handle about 10-12 lbs of shot per minute at 80 psi. The velocity of shot leaving the gun would be about 150 ft./sec.

DIRECT PRESSURE GUN.

The shot velocity is proportioned to the air pressure supplied. The shot is metered thru a separate orfice internal in the pressure system. The shot is supplied to the single jet gun which is connected by a single hose to the shot supply tank which is under the desired pressure.

A typical 3/8" diameter jet nozzle could handle about 35 lbs. of shot per minute at 80 psi. The velocity of shot leaving the gun would be about 250 ft. / sec., and the air consumption about 160 CFM. The power consumption for this amount of air would be about 25 H.P. and the blast would normally produce about .020 to .025A2 intensity.

FOR A TYPICAL LARGE AREA APPLICATION:

	One Wheel	8, 3/8" jet Direct pressure guns	24, ½" nozzle, 7/32" jet Induction guns
Intensity	.020-.025A2 @90°	.020-.025A2 @90°	.013-.015A2 @90°
Shot volume	300 lbs./ min total	288 lbs./min.total (35 lbs./min.ea.)	280 lbs./min.total (10-12 lbs./min.ea.)
Shot velocity	250 ft./sec.	250 ft./sec. @ 80 psi	150 ft./sec. @ 80 psi
Air Consumption		1280 CFM (160 CFM ea.)	1280 CFM (53 CFM ea.)
Power Req'd	15 BHP*	200 BHP*	2000 BHP*

* This is for conditions of continuous operation on a continuous work feed. If intermittent use is considered the BHP will be dependent upon size of the accumulator and cycle time of blasting.

BIBLIOGRAPHY

1. Williams, S. R., "Hardness and Hardness Measurement", Amer. Soc. for Metals, Cleveland, O., 1942, pp 45, 253, 256, 260, 267, 285, 306.
2. "Engineering", (Br.), Vol. 126, Iron and Steel Institute, London, July 6, 1928, pp 28-29,359,361. ibid. Oct. 7, 1927, p 470; Sept., 30, 1927, p420.
3. Egger, W and Diamond, G. X., "Fillet Rolling", Machine Design, Jan. 5, 1951, p 118.
4. Small, Louis; "Hardness-Theory and Practice", Part 1, Service Diamond Tool Co., Ferndale, Mich., 1960, pp 22,26,348.349.
5. O'Neill, H., "Hardness of Metals and Its Measurement", Sherwood Press, Cleveland, O., 1934, pp 16,17,129.
6. Lysaght, V. E., "Indentation Hardness Testing", Wilson Mechanical Instrument Co; Reinhold Publ., N.Y., p 26-27. 1942.
7. Miller, H. H. and Flynn, P. H., "Shot Peening Coverage", General Motors Corp, Buick Div., Flint, Mich, presented before Div. 20, S.A.E., Hot Springs, Va., Sept. 24-26, 1952.
8. "Metals Handbook"' 8th. ed., Vol. 2, Amer. Soc. for Metals, Cleveland, O., 1964, pp 399-405.
9. "Shot Peening", 7th. ed., Wheelabrator Corp., Mishawaka, Ind., 1962, pp 33,38, 64,89.
10. Straub, J. C., "Special Performance of Transmission Parts by Shot Peening", S.A.E. Paper No. 730800 presented at Milwaukee, Wisc., Sept. 10-13, 1973.
11. "S.A.E. Manual on Shot Peening", S.A.E. publication No. SP-84, S.A.E., 1952, p 4-9.
12. Almen, J. O. and Black, P. H., "Residual Stresses and Fatigue in Metals", McGraw-Hill, 1963, p154.
13. Huyett, R. B., "Shot Peening Increases Life of Machinery Parts", Parts 1 and 2, Steel Processing, Sept. 1947, pp 553-558, 573; Oct. 1947, pp 609-613,638, 647.
14. Straub, J. C., "Shot Peening in the Design of Gears", A.G.M.A., presented at The Homestead, Va., 1953 A.G.M.A. meeting, A.G.M.A. No. 101.05.
15. Halgren, J. A. and Wulpi, D. J., "Testing of Gears", presented at Milwaukee, Wisc. S.A.E. meeting, Sept. 12, 1956. S.A.E. Trans., Vol. 65, 1957.
16. Straub, J. C., "Shot Peening in Gear Design, 1964", presented at The Homestead, Hot Springs, Va., A.G.M.A. meeting of June 7-10, 1964, A.G.M.A. No. 109.13.
17. Aida, T. and Oda, S., "Bending Fatigue Strength of Gears", Bul. Japan Soc. of Mech. Engr., Vol. 9, No. 36, 1966, pp 793-806. Presented before A.G.M.A.-A.S.M.E. Symposium on gear design, San Francisco, Cal., Oct. 13, 1972.
18. Boggs, B. D. and Byrne, J. G., "Fatigue Stability of Residual Stress in Shot Peened Alloys", Metallurgical Transactions, Vol. 4, Sept. 1973, pp 2153-2157.
19. "Engineering", (Br.), Iron and Steel Inst., London, Nov. 1, 1929, pp 569-571.
20. Landau, D., "Hardness", 1st ed., The Nitralloy Corp., N.Y., Jan. 1943.

CREDIT SOURCES
FOR ILLUSTRATIONS AND TABLES

		SOURCE	SUBJECT
Fig.	1	Authors	Stresses in heating and cooling.
	2	(1), p253, fig.177	Cloudburst machine.
	3	(1), p253, fig.178	Result of cloudburst test on spotty hardness.
	4	(1), p256, fig.179	Herbert Pendulum tester.
	5	(1), p260, fig.183	Rolling ball penetration.
Tab.	I	(1), p269, tab.VII	Typical work hardening numbers.
Fig.	6	(1), p267, fig.187	Working hardening graphs, several materials.
	7	(7), p9 , fig.3	Cold work effect in Rockwell B impression.
	8	(1), p45 , fig.27	Illustration of snow plow action.
	9	(4), p349, fig.13.8	Indentation with 60° cone.
	10	(4), p349, fig.13.9	Indentation with 120° cone.
	11	(4), p348, fig.13.7	Indentation with ball.
	12	(4), p26 , fig. 2.8	Effect of ball deformation.
	13	(6), p26 , fig. 8a	A "ridging" impression.
	14	(6), p27 , fig. 8b	A "sinking" impression.
Tab.	III	(3), p118, tab. 4	Work hardenability of several steels.
Fig.	15	(8), p401, fig.8	Depth of compression layer vs intensity of peening.
	16	(10) p20 , fig.C-1	Profile of a peened surface.
	17	(7), fig.17	100% coverage (#230 shot).
	18	(7), fig.27	96% coverage (#50 grit).
	19	(8), p400, fig.5	Effect of shot size and intensity on fatigue life.
	20	(8), p405, fig.17	Almen gage and strip.
	21	(9), p 38, fig.20	Placement of gages on a crankshaft.
	22	(7), fig.14	45% courage (#230 shot).
	23	(7), fig.7	94% courage (#330 shot).
	24	(8), p401, fig.9	Courage vs exposure time.
	25	(8), p404, fig.14	Angle of impingement vs intensity.
	26	(8), p403, fig.13	Angle of impingement on compressor blade hub.
	27	(8), p399, fig.2	Rotation of gear on revolving table.
	28	(11) p7 , fig.7	Schematic of wheel blast.
	29	(11) p5 , fig.2	Induction nozzle.
	30	(7), fig.17	Compressed layer (#230shot,.020A2,100%cover).
	31	(7) fig.14	Compressed layer (#230 shot,.015A2,45% cover).
	32	(7) fig.7	Compressed layer (#330 shot,.020A2,94% cover).
	33	(12) p154, fig.12.5	Almen-Black SN curve, carburized gears.
	34	(9), p89 , fig.57	Moore SN curve, carburized gears.
	35	(12),p154, fig.12.4	Chipping of teeth by overpeening.
Tab.	II	(8), p404, tab.5	Cost of peening gears.
Tab.	IV	(13) p610-613	Power consumption in shot peening.

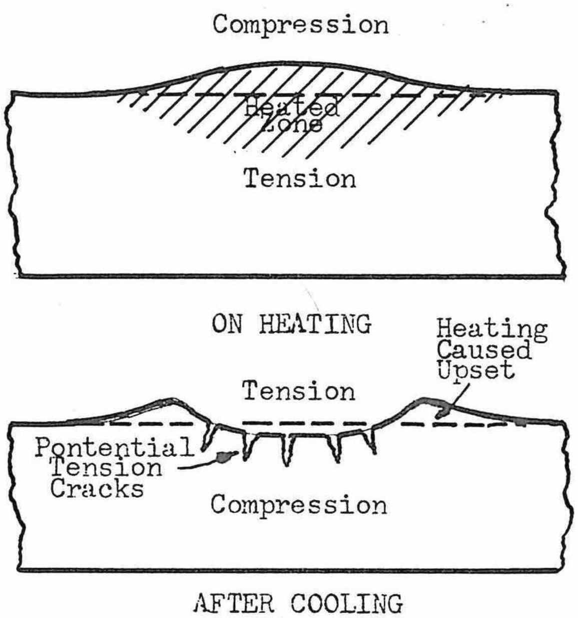


Figure 1.

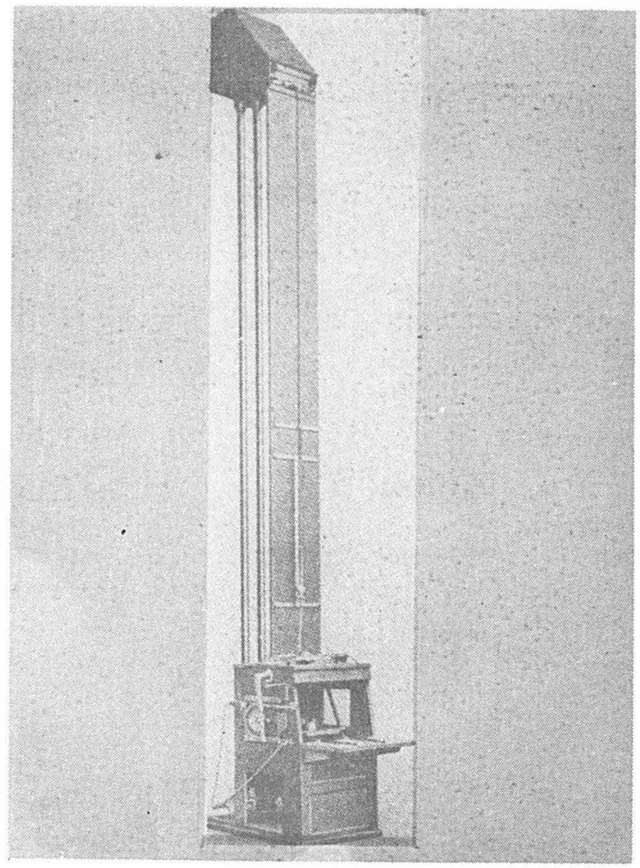


FIG. 2

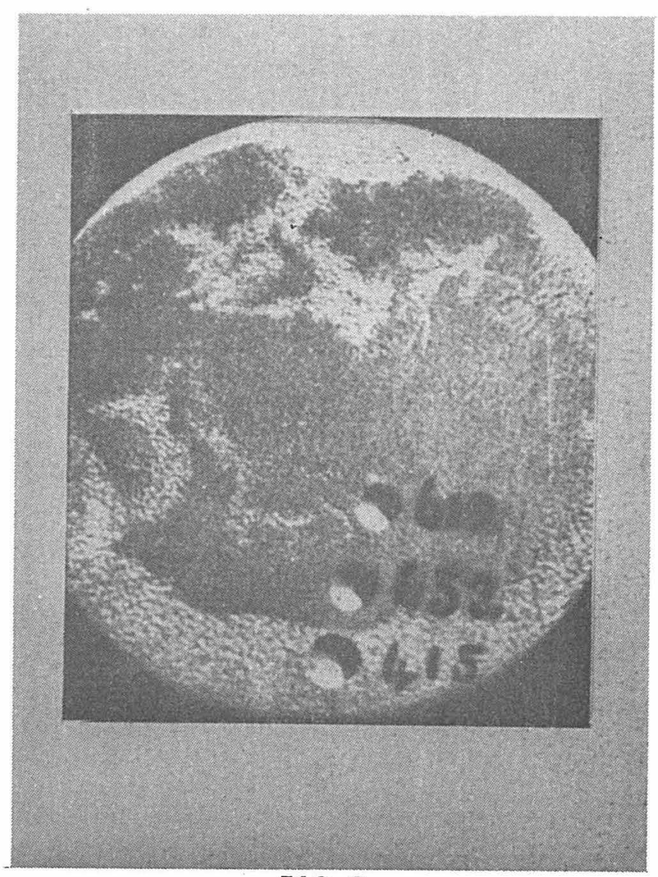


FIG. 3

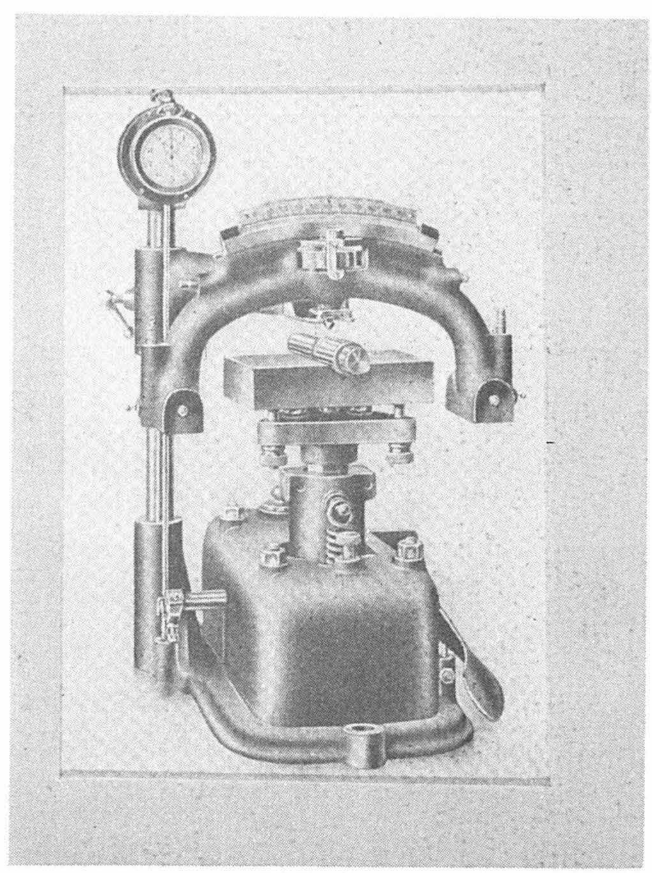
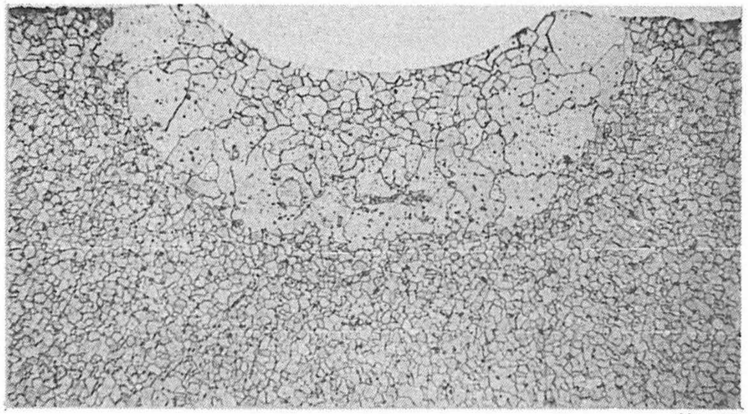


FIG. 4



X50 NITAL

PHOTOMICROGRAPH OF COLD WORK EFFECT OF ROCKWELL "B" IMPRESSION

FIGURE 7

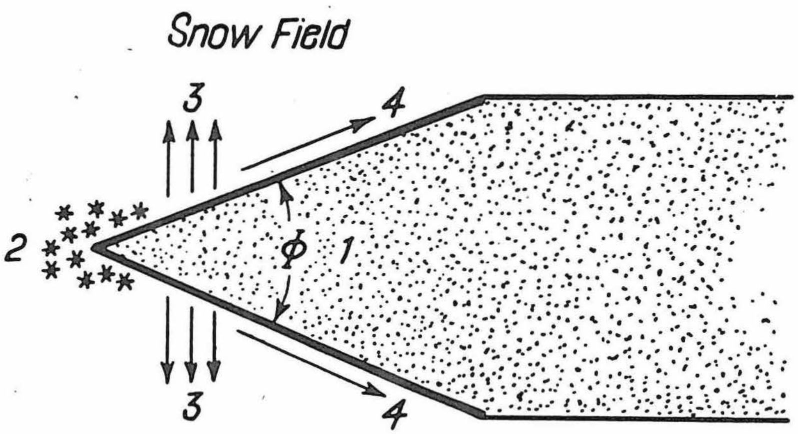


FIG. 8 —As the point of the plow pushes into the snowdrift the crystals are pulled apart. This offers resistance to penetration. The sliding of the snow crystals over each other and over the surface of the plow offers frictional resistance.

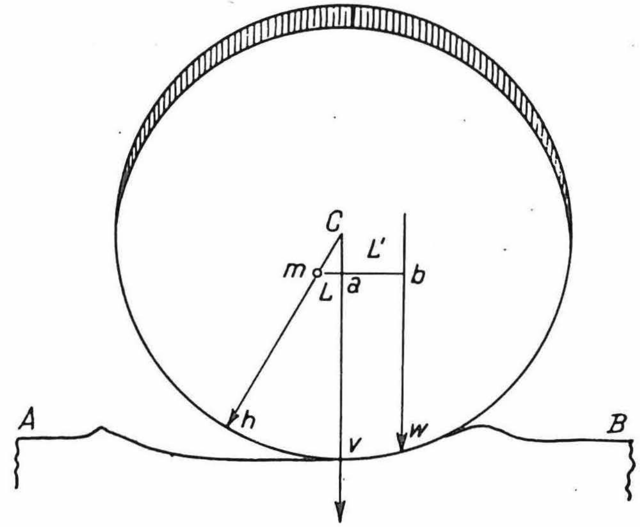


Fig. 5

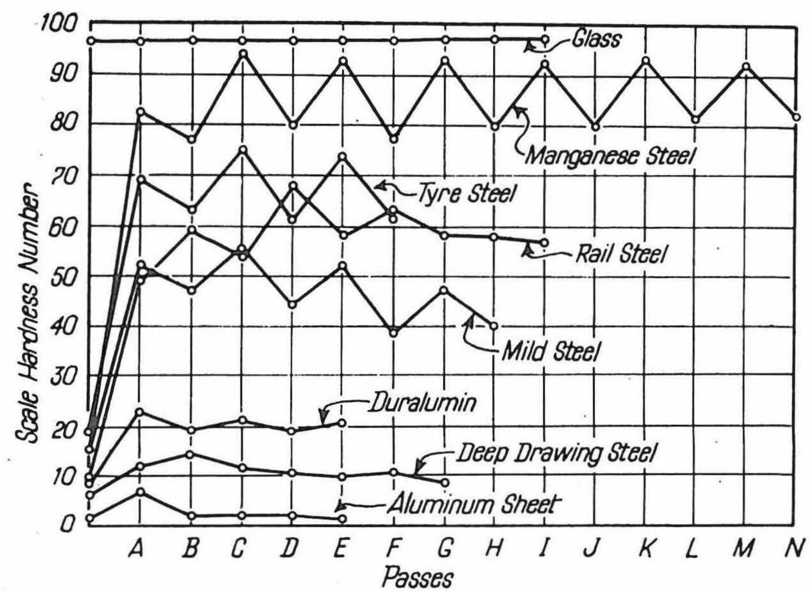
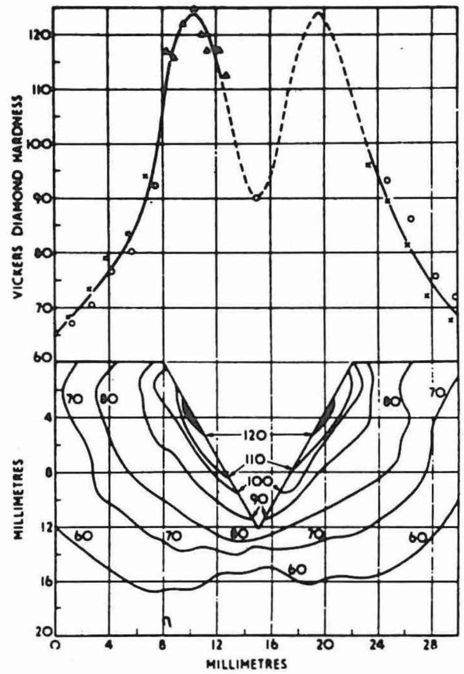
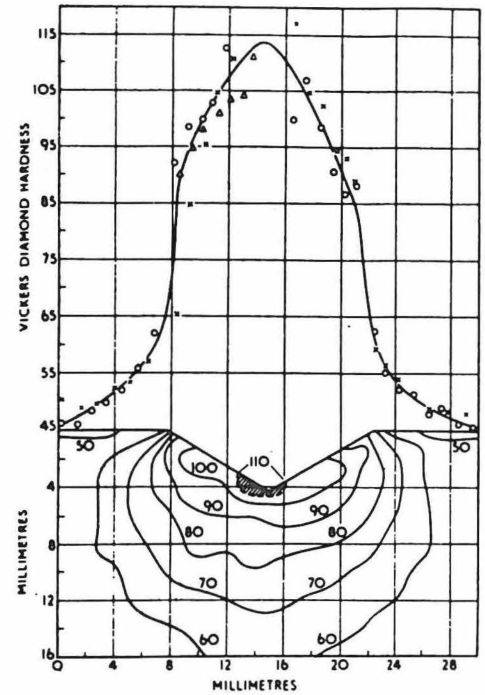


FIG. 6



Indentation in copper with 60° cone at 8640 kg.

Fig. 9



Indentation in copper with 120° cone at 7825 kg.

Fig. 10

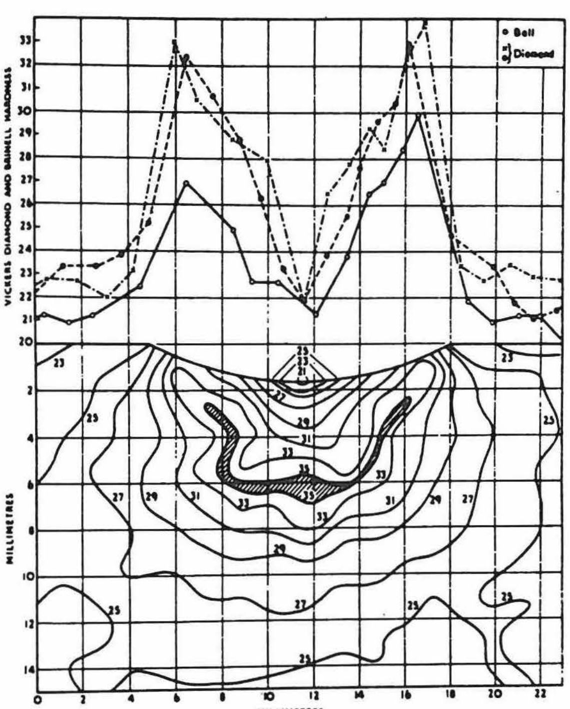
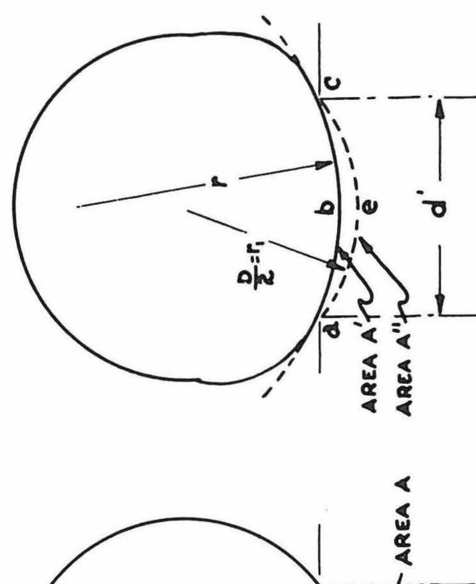


Fig. 11



Effect of deformation of the ball on the Brinell number

Fig. 12

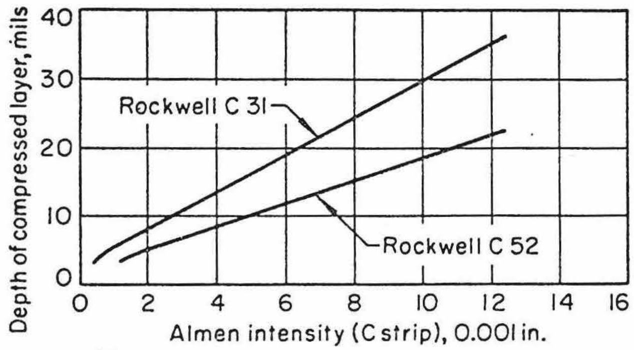


Fig. 15 Relation of depth of compressed layer to peening intensity for steel of two different hardnesses (Brodrick and Lessells, SAE Division 20, 1956)

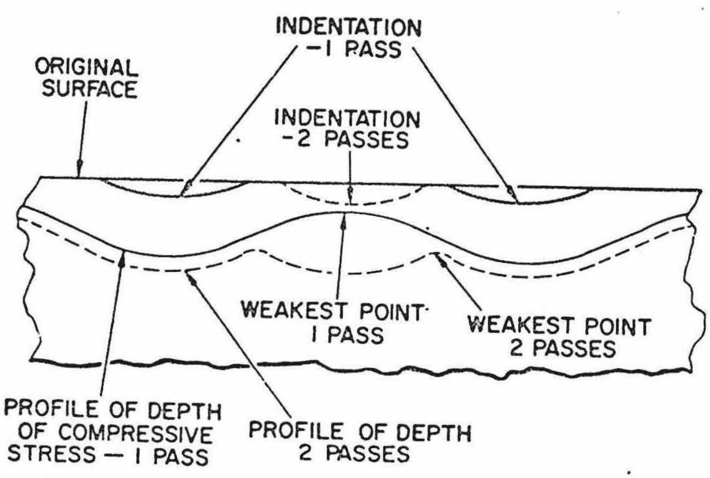


Fig. 16 - Profile of peened surface

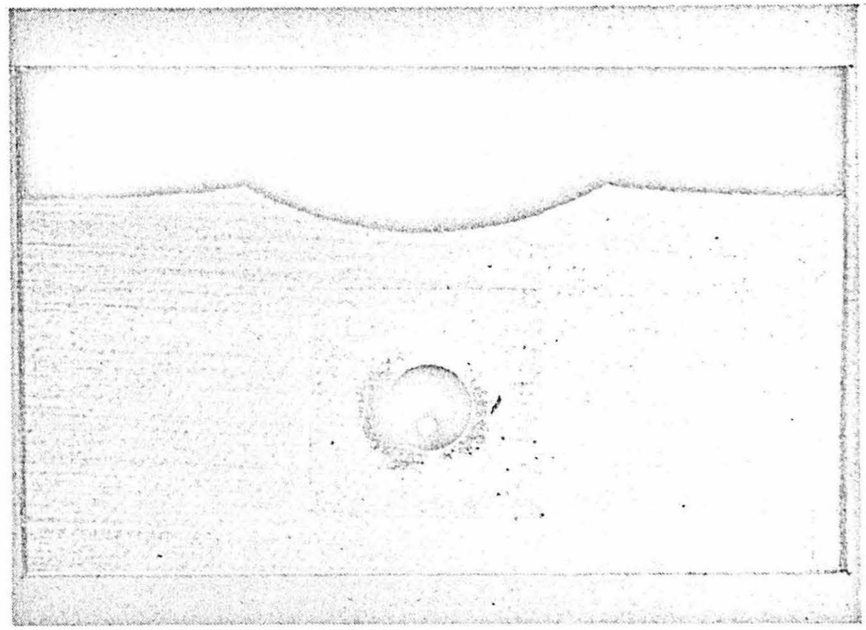


Fig. 13

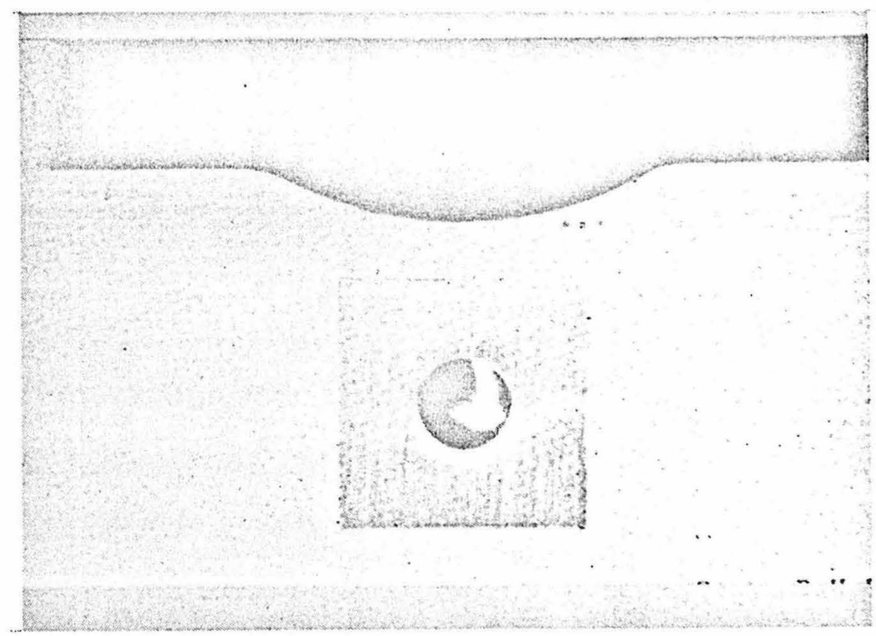


Fig. 14

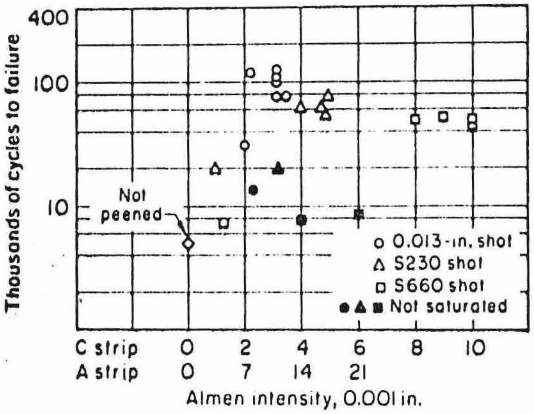


Fig. 19 Effect of shot size and peening intensity on fatigue life of steel leaf springs. Each point on the graph represents the average of four specimens. (R. L. Mattson and W. S. Coleman, Trans SAE, 62, 546; 1954)

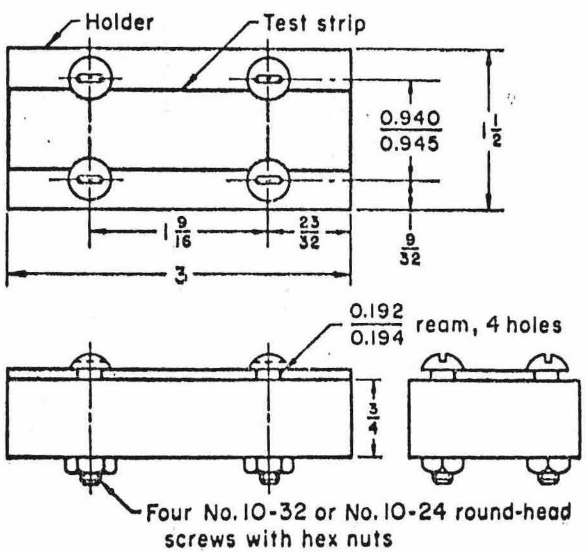


Fig. 20 Assembled test strip and holder

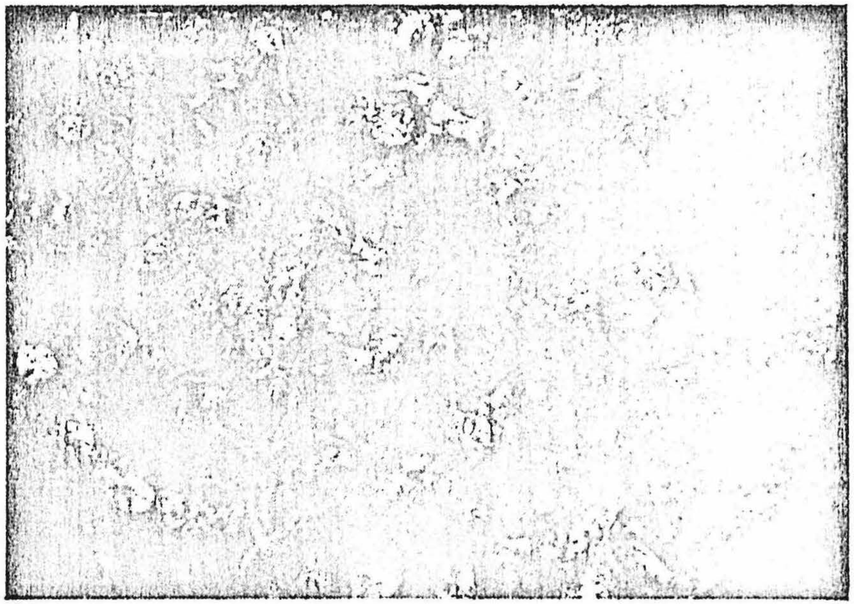


Fig. 17

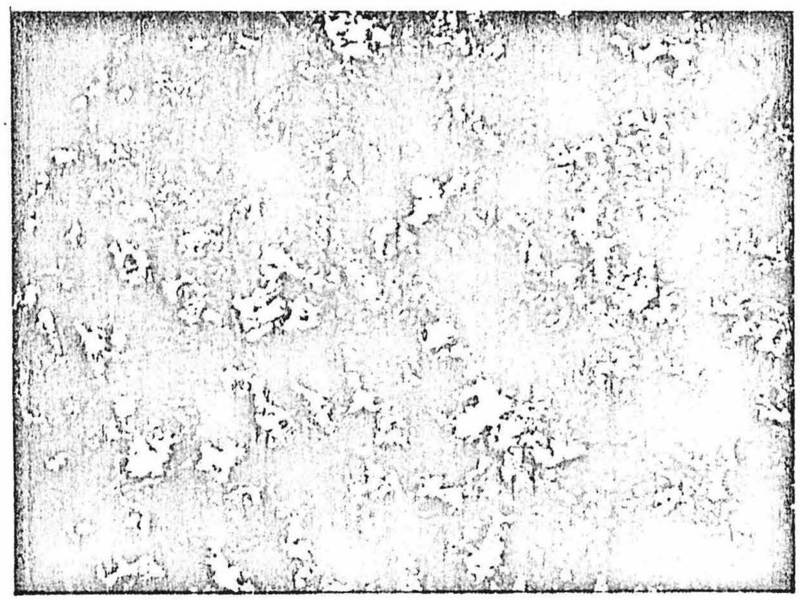


Fig. 19

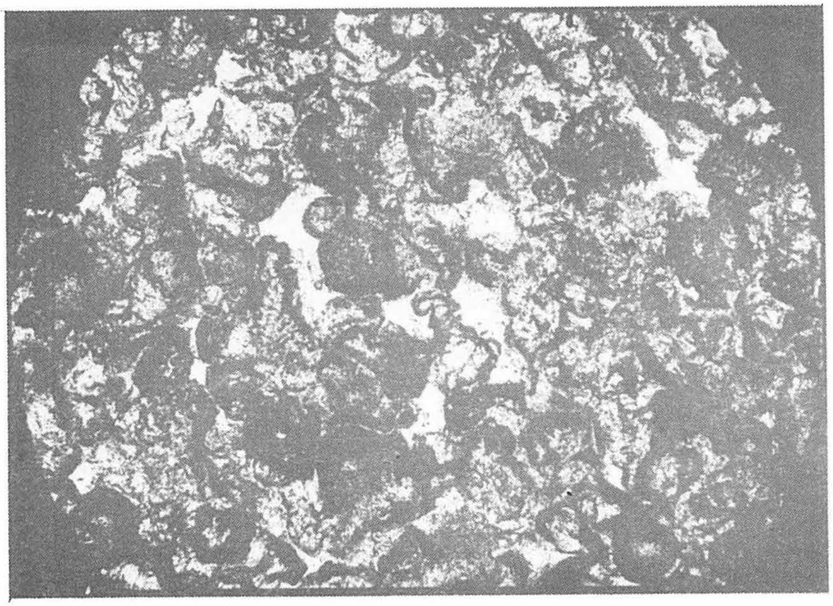


FIG. 23

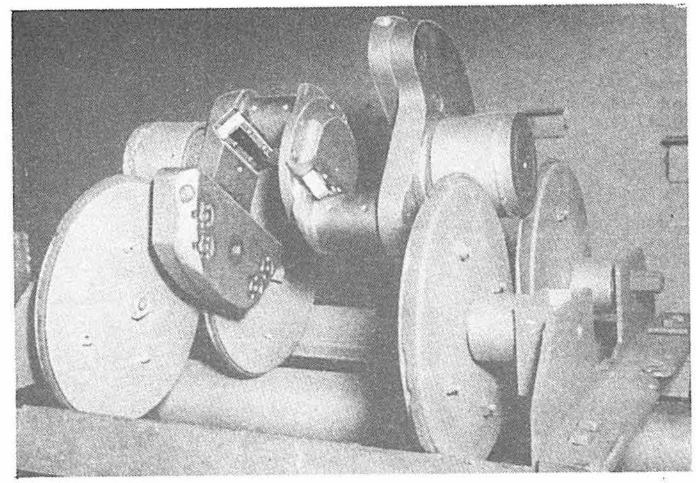


Fig. **21**

Using Almen Test Strips to Determine the Peening Intensities Produced in the Critical Areas of a Crankshaft

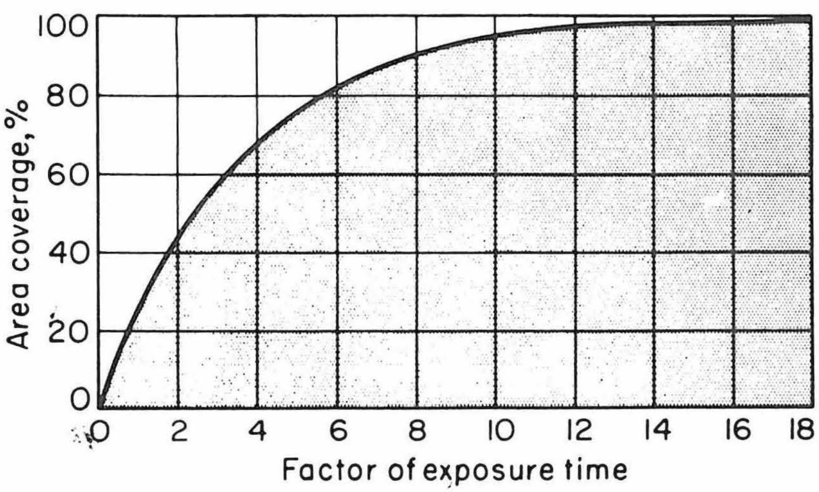


Fig.* 24 *Area coverage as a function of exposure time in shot peening

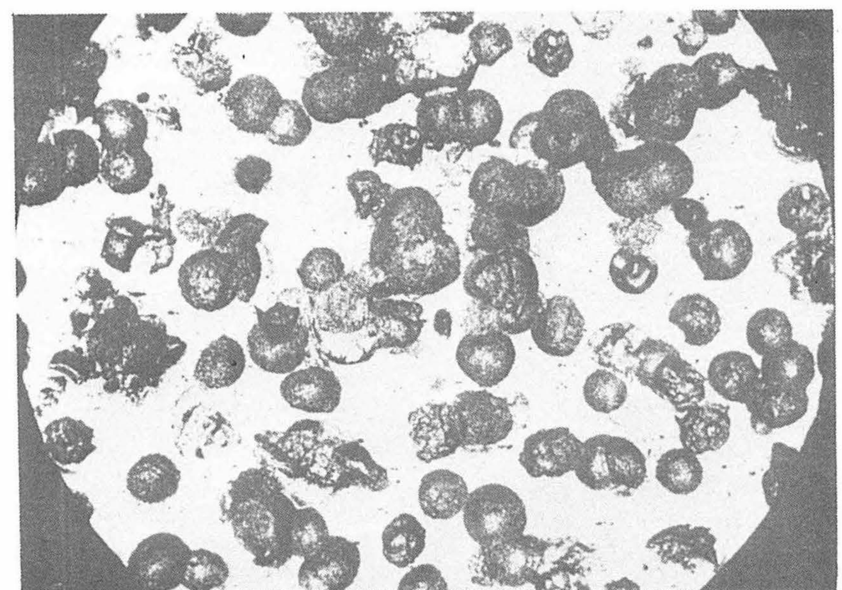
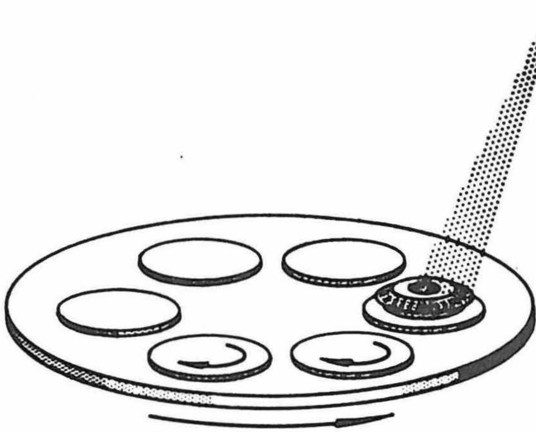
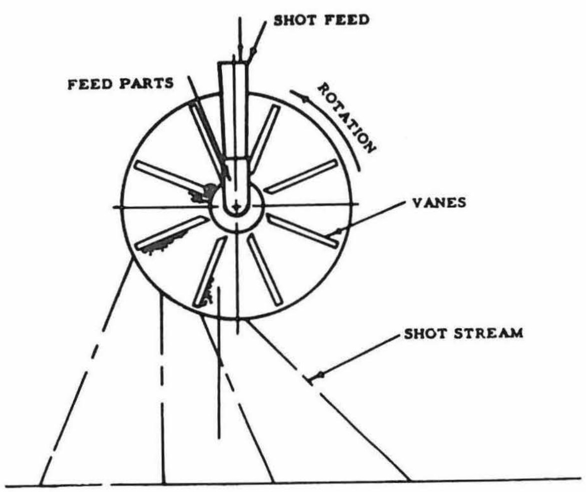


FIG. 22



Rotation of the work around a vertical axis, with circular travel

Fig. 27



CENTRIFUGAL WHEEL PEENING EQUIPMENT

Fig. 28

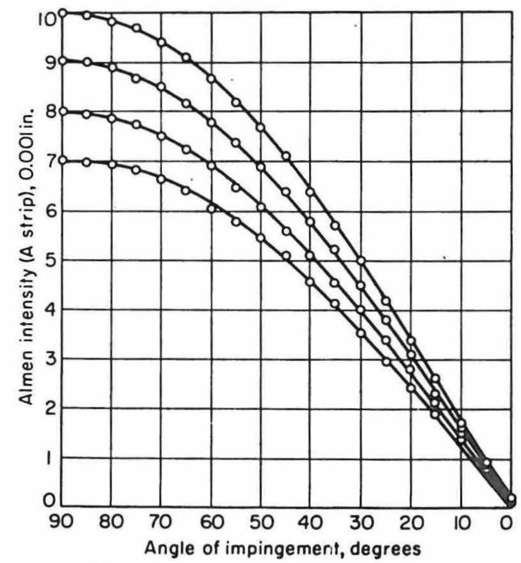


Fig. 25 Peening intensity as a function of angle of impingement

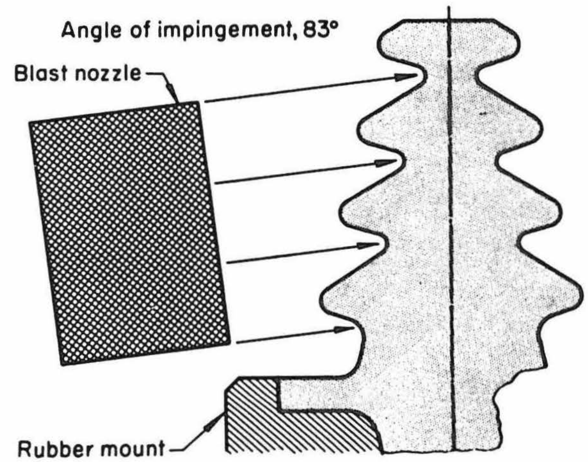
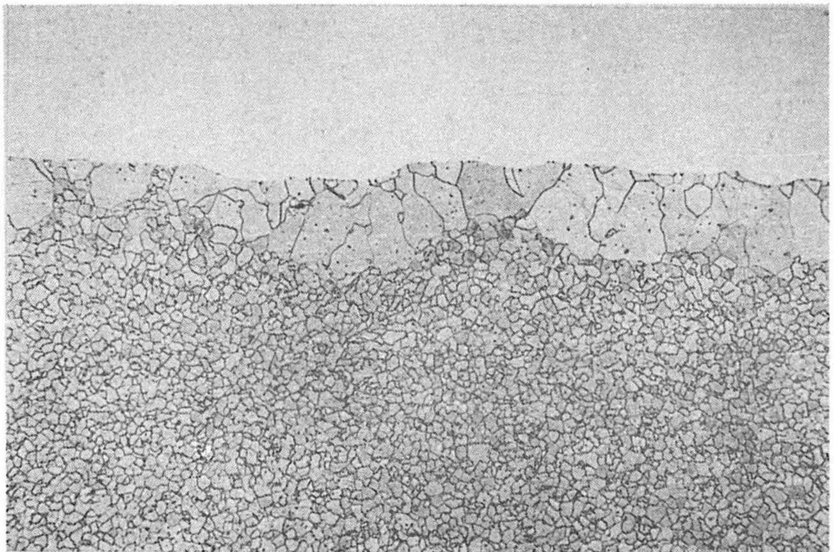
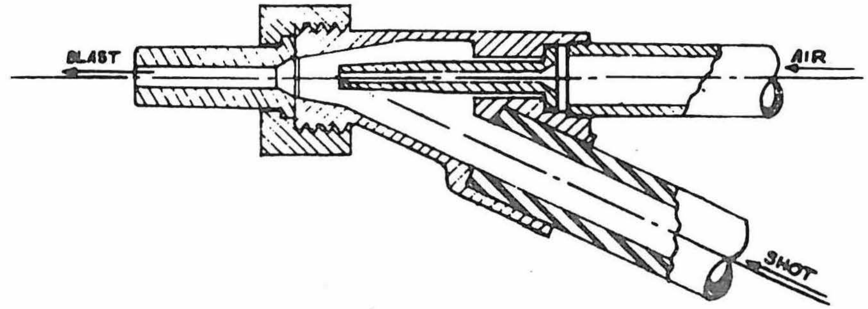


Fig. 26. Relation of nozzle angle, angle of load face, and resulting angle of impingement, in peening butt serrations of compressor blades

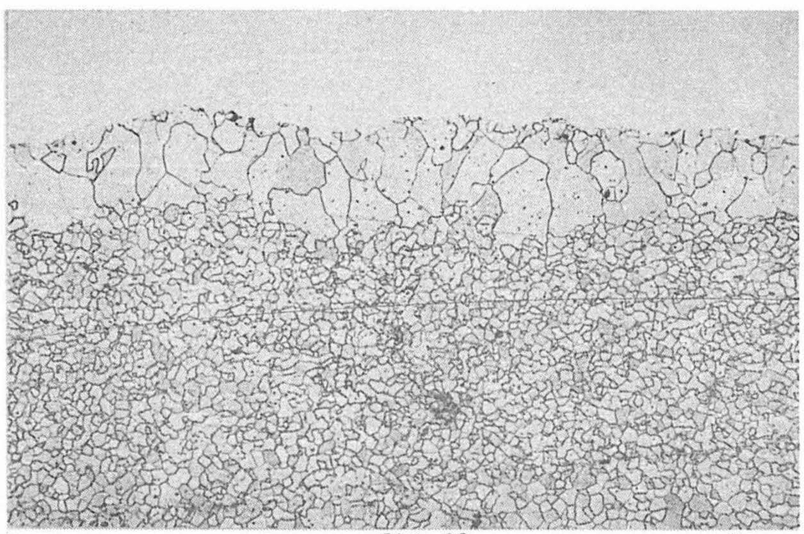


X 50 FIG 31 NITAL

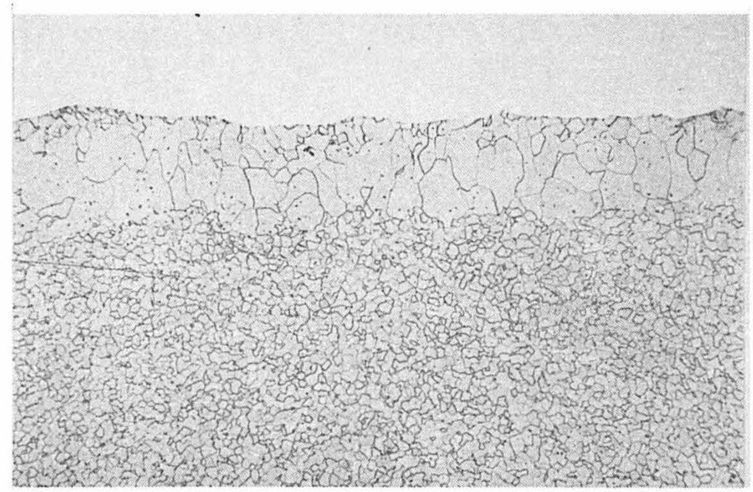


INDUCTION NOZZLE

Fig. 29



X 50 FIG 32 NITAL



X 50 FIG 30 NITAL

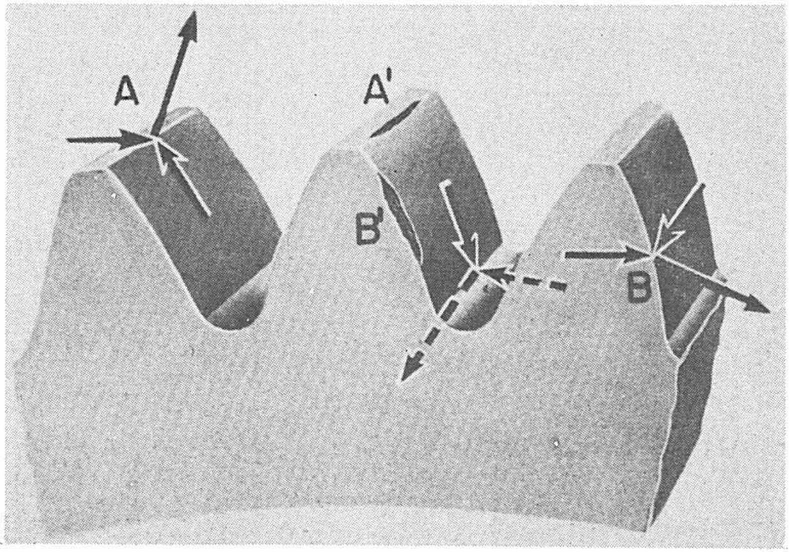


Fig. 35 Chipping of external corners.

Fig. 33 Fatigue of through-hardened cyanided, carburized, and shot-peened carburized gears.

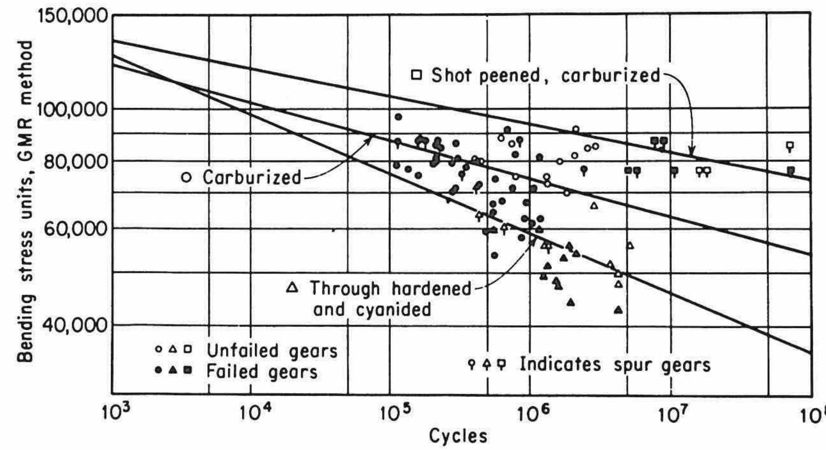
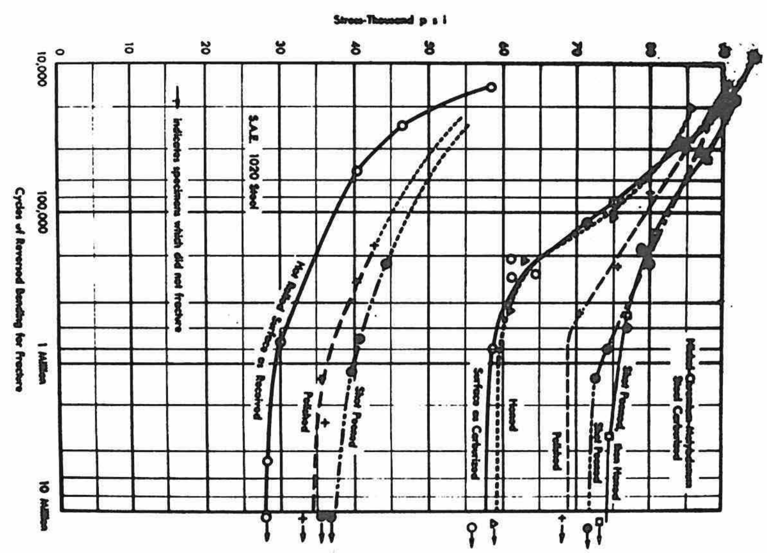


Table 11 Cost of Shot Peening Carburized and Hardened 8620 Steel Gears (Example 12) (a)

Cost factor	Cost Per year	Cost Per hour
Original investment $80,000		
Amortization (over 8 years)..	$ 10,000	$ 1.45
Maintenance materials	6,900	1.00
Maintenance labor ($2 per hr)	1,200	0.17
Shot (at $220 per ton) (b)....	36,000	5.22
Power (67 hp, 1¢ per hp-hr)..	4,630	0.67
Production labor (c)	41,400	6.00
Total	$100,130	$14.51
Peening cost per gear $0.063		

(a) Based on peening for 23 hr per day, 6 days per week, 50 weeks (6900 hr) per year. Production rate, 230 gears per hour (1,587,000 per year). (b) Cast steel shot (size, S230; hardness, Rockwell C 54 to 60). (c) Two men for loading and one for unloading, at $2 per hr.



Typical S-N Diagrams for Two Steels with Several Different Surface Treatments
FIG 34

BIBLIOGRAPHY

of AGMA (new orleans) paper by PEC + REW

1. Williams, S. R., "Hardness and Hardness Measurement", Amer. Soc. for Metals, Cleveland, O., 1942, pp 45, 253, 256, 260, 267, 285, 306.
2. "Engineering", (Br.), Vol. 126, Iron and Steel Institute, London, July 6, 1928, pp 28-29,359,361. ibid. Oct. 7, 1927, p 470; Sept., 30, 1927, p420.
3. Egger, W and Diamond, G. X., "Fillet Rolling", Machine Design, Jan. 5, 1951, p 118.
4. Small, Louis; "Hardness-Theory and Practice", Part 1, Service Diamond Tool Co., Ferndale, Mich., 1960, pp 22,26,348.349.
5. O'Neill, H., "Hardness of Metals and Its Measurement", Sherwood Press, Cleveland, O., 1934, pp 16,17,129.
6. Lysaght, V. E., "Indentation Hardness Testing", Wilson Mechanical Instrument Co; Reinhold Publ., N.Y., p 26-27. 1942.
7. Miller, H. H. and Flynn, P. H., "Shot Peening Coverage", General Motors Corp, Buick Div., Flint, Mich, presented before Div. 20, S.A.E., Hot Springs, Va., Sept. 24-26, 1952.
8. "Metals Handbook"' 8th. ed., Vol. 2, Amer. Soc. for Metals, Cleveland, O., 1964, pp 399-405.
9. "Shot Peening", 7th. ed., Wheelabrator Corp., Mishawaka, Ind., 1962, pp 33,38, 64,89.
10. Straub, J. C., "Special Performance of Transmission Parts by Shot Peening", S.A.E. Paper No. 730800 presented at Milwaukee, Wisc., Sept. 10-13, 1973.
11. "S.A.E. Manual on Shot Peening", S.A.E. publication No. SP-84, S.A.E., 1952, p 4-9.
12. Almen, J. O. and Black, P. H., "Residual Stresses and Fatigue in Metals", McGraw-Hill, 1963, p154.
13. Huyett, R. B., "Shot Peening Increases Life of Machinery Parts", Parts 1 and 2, Steel Processing, Sept. 1947, pp 553-558, 573; Oct. 1947, pp 609-613,638, 647.
14. Straub, J. C., "Shot Peening in the Design of Gears", A.G.M.A., presented at The Homestead, Va., 1953 A.G.M.A. meeting, A.G.M.A. No. 101.05.
15. Halgren, J. A. and Wulpi, D. J., "Testing of Gears", presented at Milwaukee, Wisc. S.A.E. meeting, Sept. 12, 1956. S.A.E. Trans., Vol. 65, 1957.
16. Straub, J. C., "Shot Peening in Gear Design, 1964", presented at The Homestead, Hot Springs, Va., A.G.M.A. meeting of June 7-10, 1964, A.G.M.A. No. 109.13.
17. Aida, T. and Oda, S., "Bending Fatigue Strength of Gears", Bul. Japan Soc. of Mech. Engr., Vol. 9, No. 36, 1966, pp 793-806. Presented before A.G.M.A.-A.S.M.E. Symposium on gear design, San Francisco, Cal., Oct. 13, 1972.
18. Boggs, B. D. and Byrne, J. G., "Fatigue Stability of Residual Stress in Shot Peened Alloys", Metallurgical Transactions, Vol. 4, Sept. 1973, pp 2153-2157.
19. "Engineering", (Br.), Iron and Steel Inst., London, Nov. 1, 1929, pp 569-571.
20. Landau, D., "Hardness", 1st ed., The Nitralloy Corp., N.Y., Jan. 1943.

CREDIT SOURCES
FOR ILLUSTRATIONS AND TABLES

		SOURCE	SUBJECT
Fig.	1	Authors	Stresses in heating and cooling.
	2	(1), p253, fig.177	Cloudburst machine.
	3	(1), p253, fig.178	Result of cloudburst test on spotty hardness.
	4	(1), p256, fig.179	Herbert Pendulum tester.
	5	(1), p260, fig.183	Rolling ball penetration.
Tab.	I	(1), p269, tab.VII	Typical work hardening numbers.
Fig.	6	(1), p267, fig.187	Working hardening graphs, several materials.
	7	(7), p9 , fig.3	Cold work effect in Rockwell B impression.
	8	(1), p45 , fig.27	Illustration of snow plow action.
	9	(4), p349, fig.13.8	Indentation with 60° cone.
	10	(4), p349, fig.13.9	Indentation with 120° cone.
	11	(4), p348, fig.13.7	Indentation with ball.
	12	(4), p26 , fig. 2.8	Effect of ball deformation.
	13	(6), p26 , fig. 8a	A "ridging" impression.
	14	(6), p27 , fig. 8b	A "sinking" impression.
Tab.	III	(3), p118, tab. 4	Work hardenability of several steels.
Fig.	15	(8), p401, fig.8	Depth of compression layer vs intensity of peening.
	16	(10) p20 , fig.C-1	Profile of a peened surface.
	17	(7), fig.17	100% coverage (#230 shot).
	18	(7), fig.27	96% coverage (#50 grit).
	19	(8), p400, fig.5	Effect of shot size and intensity on fatigue life.
	20	(8), p405, fig.17	Almen gage and strip.
	21	(9), p 38, fig.20	Placement of gages on a crankshaft.
	22	(7), fig.14	45% courage (#230 shot).
	23	(7), fig.7	94% courage (#330 shot).
	24	(8), p401, fig.9	Courage vs exposure time.
	25	(8), p404, fig.14	Angle of impingement vs intensity.
	26	(8), p403, fig.13	Angle of impingement on compressor blade hub.
	27	(8), p399, fig.2	Rotation of gear on revolving table.
	28	(11) p7 , fig.7	Schematic of wheel blast.
	29	(11) p5 , fig.2	Induction nozzle.
	30	(7), fig.17	Compressed layer (#230shot,.020A2,100%cover).
	31	(7) fig.14	Compressed layer (#230 shot,.015A2,45% cover).
	32	(7) fig.7	Compressed layer (#330 shot,.020A2,94% cover).
	33	(12) p154, fig.12.5	Almen-Black SN curve, carburized gears.
	34	(9), p89 , fig.57	Moore SN curve, carburized gears.
	35	(12),p154, fig.12.4	Chipping of teeth by overpeening.
Tab.	II	(8), p404, tab.5	Cost of peening gears.
Tab.	IV	(13) p610-613	Power consumption in shot peening.