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Mechanical and Metallurgical Advantages

BY this time it is apparent that some control must be exercised over shot peening operations if the surface layer of the design members is to be uniformly and adequately cold worked from the standpoint of obtaining beneficial increase in fatigue resistance. The expression "shot blasting" is usually associated with cleaning or descaling operations where control of the operation is anything but critical. The phrase "shot peening" has been designated as the method employed for surface treatment when increased fatigue resistance is desired, although the cleaning operation may be obtained simultaneously. Equipment in both cases is much the same except for refinements which facilitate definite control of the peening operation to meet certain specifications. One essential difference is that peening equipment requires the use of an adequate separator for removing the broken shot as too fine particles are detrimental or do not contribute to increased fatigue resistance.

Two principal types of machines are in general use, namely, the air blast and the mechanical blast. A third type, although used now principally for honing, is the liquid blast.

Instrumentation for measuring the degree of shot peening being given the work piece was a problem to which Almen[k] devoted much painstaking development work. A very ingenious and simple means was evolved as shown in Fig. 21 whereby a flat strip[l] of steel is attached to a jig block. This assembly is fastened to the critical area of the part passing under the shot stream so that one side of the strip is peened. The strip is then removed from the block and located on the dial indicator gage shown in Fig. 22 to measure the change in longitudinal curvature[m] of the strip. Being cold worked on one side only, the strip assumes an arc shape and the height of this arc is a measure of the degree of shot peening. It is necessary to know how the arc height obtained from the strip correlates with fatigue resistance. This correlation can only be developed by fatigue tests being made on the actual parts until sufficient background of data may be accumulated.

While this instrumentation in its present form leaves much to be desired, it is the best available. The sensitivity of the test is low in that for large variations in peening conditions the changes in arc height values may only be a few thousandths of an inch and yet large differences in fatigue resistance may result. It should not be inferred that maximum arc height connotes optimum fatigue resistance. Considerable doubt exists

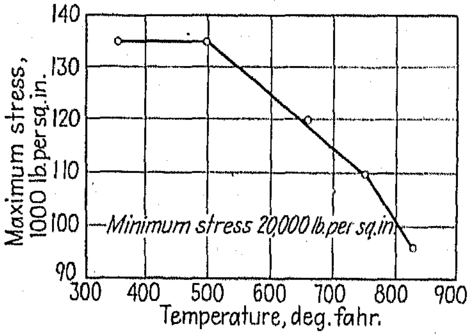

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FIG. 20—Effect of heat on shot-blasted springs. (Zimmerli)

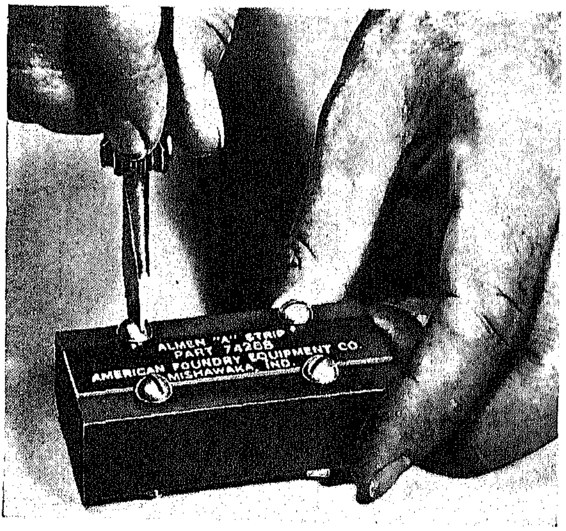

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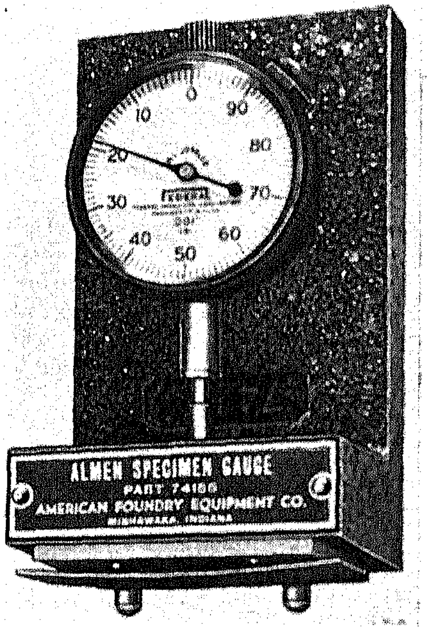
FIG. 21—Shot intensity calibrating strip being attached to jig block which is passed through blast with parts being peened.

RIGHT

FIG. 22—Calibration strip in position on dial indicator to measure the arc height.



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[l] *This strip is ¾ in. wide by 3 in. long and comes in two thicknesses designated as the A strip which is 0.051 in. thick and the C strip 0.0938 in., Rc = 44-50.*

[m] *Change in longitudinal curvatures is measured over a fixed gage length of 1.3 in. and is designated as the arc height. Two types of gages Nos. 1 and 2 are used although the latter type is preferred because it measures the curvature from the unpeened side of the strip as shown in Fig. 22. The No. 1 gage measures curvature from the peened side and the surface roughness and transverse curvature interferes with accurate arc height measurements. Arc height readings are designated, for example, 0.008A2 which means that the height of arc is 0.008 in. on a 0.51-in. thick strip using No. 2 type of gage.*

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# of SHOT PEENING

By O. J. HORGER

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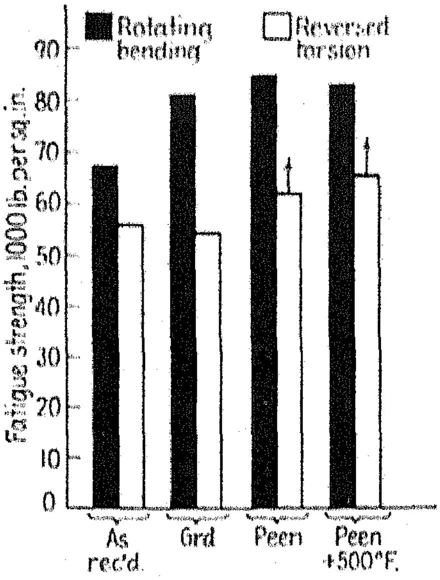
. . . The second section of a two-part article appraising the technical and economic utility of compressing the surface layers of design members as a means of greatly improving their fatigue resistance. Last week the author covered the history of shot peening, the peening of springs, and tempering after peening. Herein, attention is directed to control of shot peening, treatment of light alloys, shot size and time, liquid blast, and the peening of gears, tank parts and crankshafts.

among several investigators as to whether the arc height values are significant as an index of fatigue life. Likewise improvements in shot material and quality as well as peening equipment would be welcome. The process of peening is a relatively new field and given impetus as a result of requirements of the armed services so that the immediate wide demand for this equipment has grown faster than development and improvements would permit.

Peening Steels and Light Alloys

Forerunner of shot peening experiments reported in the literature were made by Weibel[11] on 0.225-in. diameter tempered Swedish wire. He tumbled the wire test pieces under an air blast 40 lb. per sq. in., which produced beneficial fatigue results as given in Fig. 23. Even this type of peening gave an endurance limit in rotating bending which was 24 per cent to 27 per cent greater than in the as-received condition. Endurance limit in torsion could not be obtained on the peened wire because his specimens the grips. The arrows on the torsion always developed fatigue failure in values in Fig. 23 indicate that the fatigue strength is greater than that shown by an undetermined amount.



ABOVE

FIG. 23—Effect of surface conditions on rotating bending and reversed torsional fatigue resistance of tempered Swedish wire. (All peening done on as-received wire—Weibel.)

Wiegand[10] investigated the influence of different mechanical surface preparations on the fatigue strength of plain specimens ¼ in. in diameter from a heat-treated high-strength alloy steel*. His results are shown in Table III, and from this he concluded that there is no need for expensive polishing operations on such a high-grade steel as used in engine construction when equal fatigue resistance may be obtained by shot blasting the rough surface in C.

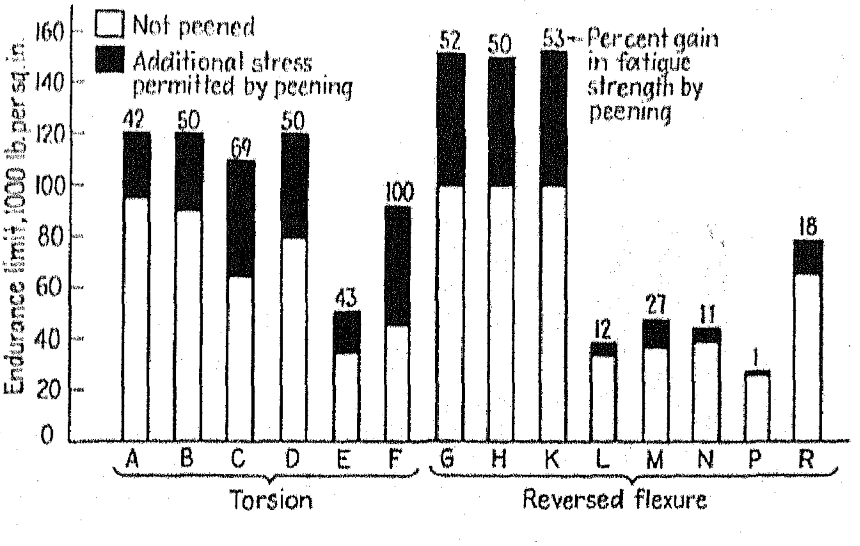
Weigand[10] also studied the influence of shot blasting on the fatigue resistance of light alloys and his results are quoted in Table IV. He attributed the scatter in fatigue resistance obtained with electron castings as be-

TABLE III

Influence of Surface Preparation on Fatigue Strength

Surface Finish	Rotating Bending Fatigue Strength, Lb. Per Sq. In.
(a) Ground and polished 00	79,650
(b) Lapped	80,350
(c) Roughed with emery cloth No. 24	68,850
(d) Sand blasted, 45 lb. per sq. in. pressure, 20 min.	72,500
(e) Polished and shot blasted, 75 lb. per sq. in. pressure, 30 min.	81,100
(f) Roughed as in (c) and shot blasted 75 lb. per sq. in. pressure, 30 min.	79,650

FIG. 24—Effect of shot peening on endurance limit of various steels: (A) 0-0.85 per cent C spring wire (1); (B) SAE 1095 music wire (1); (C) 18-8 stainless wire (1); (D) 13-2 stainless wire (1); (E) phos. bronze, SAE 81 (1); (F) 18-8 stainless (Wahl 24); (G) NE 9470, carburized (24); (H) SAE 4032, carburized (24); (K) NE 9420, carburized (24); (L*) SAE 1020 plate (24); (M*) SAE 1050 plate (24); (N*) SAE 1045 annealed (18); (P*) Armco iron (18); (R*) X4340 Q & T (18). Minimum torsional stress 20,000 lb. per sq. in. except for F, which was zero. *Surface polished previous to peening—others not polished.



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* 0.3 *per cent C, 2 Cr,* 0.3 *Mo, and* 2 *per cent Ni; ultimate strength* 160,000 *lb. per sq. in.; elongation* 9 *per cent, basis* 10 *million stress reversals.*

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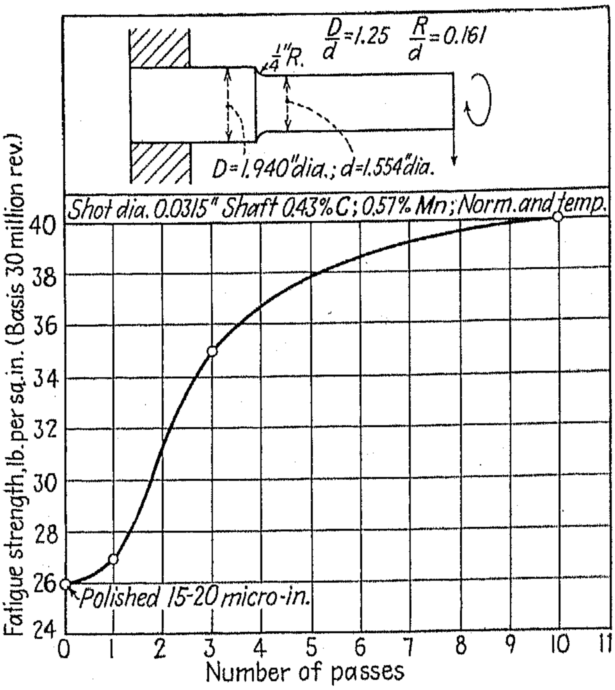

FIG. 25—Effect of number of passes under shot blast stream on the fatigue strength of shot peened shafts with ¼-in. fillet.

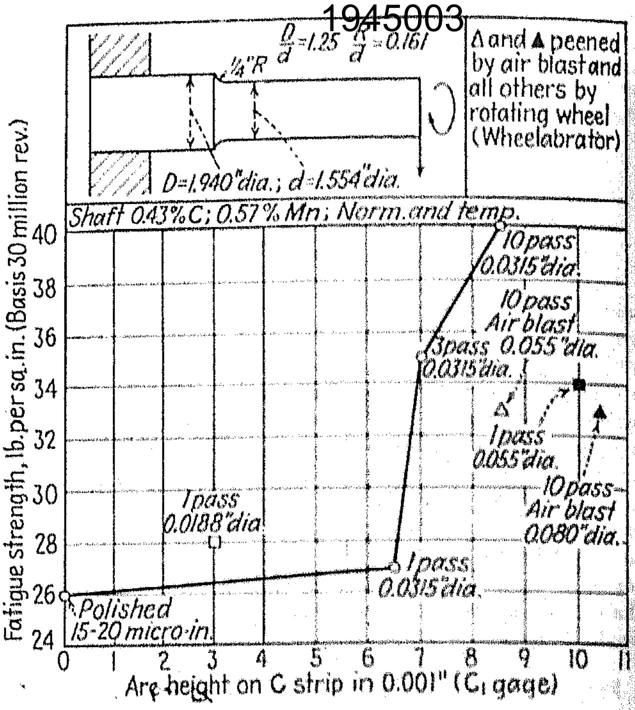

FIG. 26—Effect of shot size and arc height on the fatigue strength of shot peened shafts with ¼-in. fillet.

ing no doubt due to irregularities in the castings. His conclusions stated that the endurance of aluminum and magnesium alloys could be improved as well as production time reduced for surface finish operations if such parts were shot blasted.

Further evidence of the beneficial influence of peening on fatigue resistance is shown in Fig. 24 which represents the results of several investigators. Also Lessells and Murray[18] shot peened ¼-in. diameter plain fatigue specimens of quenched and tempered SAE 1045 and 9260 steels,[p] not shown in Fig. 24. They reported slightly lower endurance values for those plain specimens ground, polished, and peened than for those having a ground and polished surface. This reduction in fatigue resistance may be explained by improper blasting conditions, or as Lessells reported by the unfavorable surface stresses remaining from heat treatment.

TABLE V
Accelerated Testing to Show Life Improvement

Type of Part	Life Improvement Per Cent
Welded joints	310
Steering knuckles	475
Engine crank shafts	900
Helical springs	1370
Transmission main shafts	520
Hypoid gears	600
U joint crosses	520

It will be noted that improvement in fatigue resistance due to shot peening has generally been expressed here in terms of endurance limit values; that is, allowable stresses for long life of say 10 million stress reversals. In some types of equipment parts, such as automobile and ordnance equipment, it is common to relate this improvement in terms of comparable life for a specific stress. Using a life basis infers a knowledge of the stresses in operation, and while these are seldom known it is customary to conduct accelerated types of fatigue tests. In order to fail parts relatively soon, a stress is used in the test which

---

[p] *SAE* 1045 *steel had ultimate strength of* 152,700 *lb. per sq. in.,* 17 *per cent elongation;* 56 *per cent reduction in area, Brinell* 311. *SAE* 9620 *steel had ultimate strength of* 322,000 *lb. per sq. in.,* 7 *to* 14 *per cent reduction in area, Brinell* 548-570.

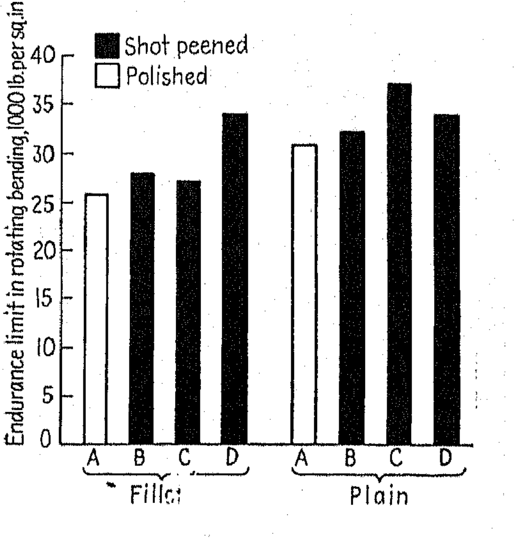

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FIG. 27 — Endurance limit vs. shot size for only one pass of filleted and plain 1½ in. diameter shafts under shot stream. (A) polished; (B) smooth turn and peened, 0.019 in. shot, arc ht. 0.003C1; (C) smooth turn and peened, 0.032 in. shot, arc ht. 0.006C1; (D) smooth turn and peened, 0.055 in. shot, arc. ht. 0.010C1.

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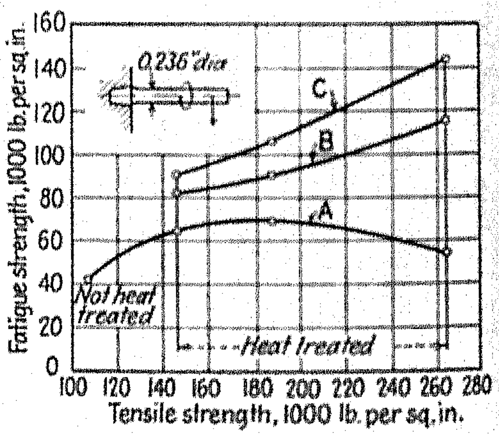

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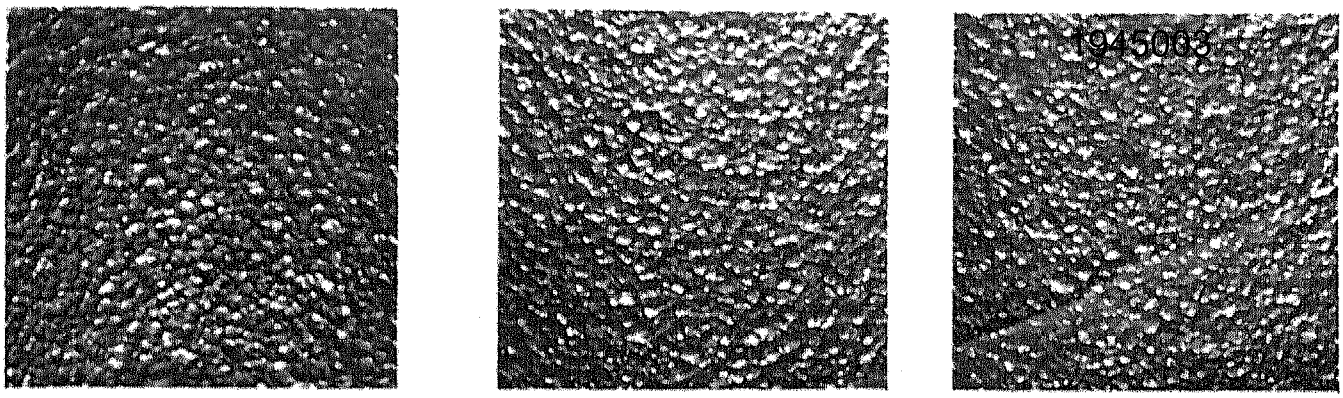
FIG. 28. Increase of fatigue strength by shot blasting (by Lupfert); 0.45 per cent C, 1.0 per cent Mn steel, quenched and tempered; (A) not shot blasted; (B) blasted with coarse steel shot; (C) blasted with fine steel shot.

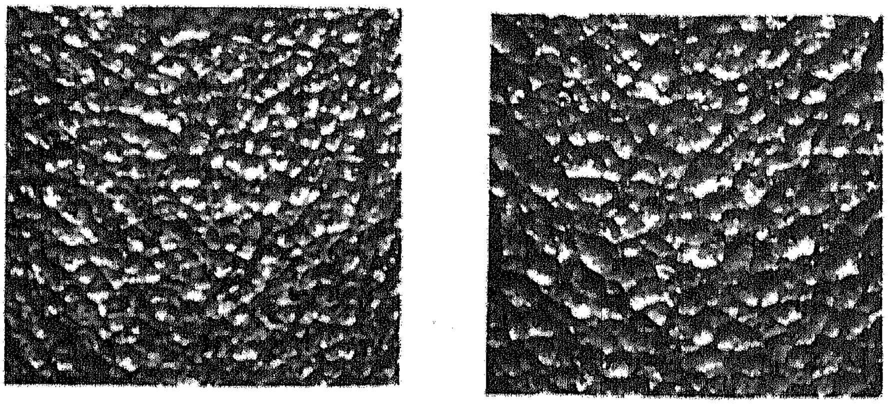


ARC HT. .0065" C1; .0175" A1
1 PASS

ARC HT. .007" C1; .018" A1
3 PASSES

ARC HT. .009" C1; .017" A1
10 PASSES

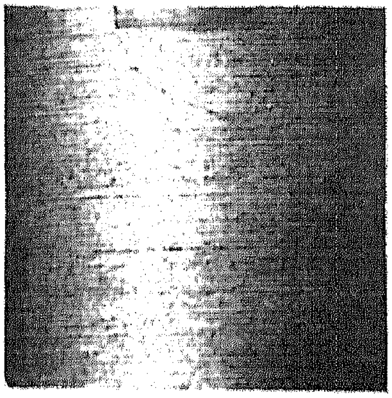
SURFACE OF SPECIMENS (X5) SHOT PEENED ON WHEELABRATOR USING .0315" DIA. SHOT.



ARC HT. .0085" C1; .014" C2
SHOT DIA. .055"-.060"

ARC HT. .0105" C1; .017" C2
SHOT DIA. .080"-.093"

SURFACE OF SPECIMENS (X5) SHOT PEENED WITH AIR BLAST.



SMOOTH TURNED SURFACE
(X5)

CONDITION OF SPEC. BEFORE SHOT PEENING.

Fig. 29—Surface finish under different peening conditions on SAE 1045.

is considerably above the endurance limit value. Depending upon the stress level chosen, life comparison values are obtained from unity to as high as infinity. Almen[7] has shown how such accelerated tests have given large increases in life through shot peening, as shown in Table V.

In any event such a life basis is often justified since it is an indication of how shot peened members will resist occasional high stresses generally found present in the operation of most equipment. It is plausible that a high stress due to infrequent overloads initiate the fatigue fracture in service and then the normal operating stresses propagate the minute crack to complete failure. A knowledge of the endurance limit is essential, however, if long life to the part is expected in service.

Shot Size and Time

Too little systematic data exist as to the influence of shot size, time, and other factors on the fatigue resistance. In fact, much fatigue data already available lose some of their significance because of the absence of specifications concerning the conditions of blasting.

Zimmerli[8] shows the affect of blasting time on endurance values in Fig. 5 for valve springs. Fig. 25, by the author[13], also compares endurance values versus the number of passes for 1½-in. diameter filleted shafts of SAE 1045 steel, normalized and

TABLE IV

Influence of Shot Blasting on Fatigue Resistance of Light Alloys

Material	Surface Finish	Rotating Bending Fatigue Strength, Lb. Per Sq. In.
3115.5 duralumin 69,700 lb. per sq. in. ultimate 38,400 lb. per sq. in. Y. P. (0.2)	Fine Turned	17,100
	Fine Turned and Shot Blasted	19,900
Electron AZ.31 41,200 lb. per sq. in. ultimate 14,200 lb. per sq. in. Y. P. (0.2)	Fine Turned	13,500
	Fine Turned and Shot Blasted	17,100
Electron casting AZG	Fine Turned	5700 to 8500
19,200 to 32,700 lb. per sq. in. ultimate strength	Fine Turned and Shot Blasted	8500 to 9100

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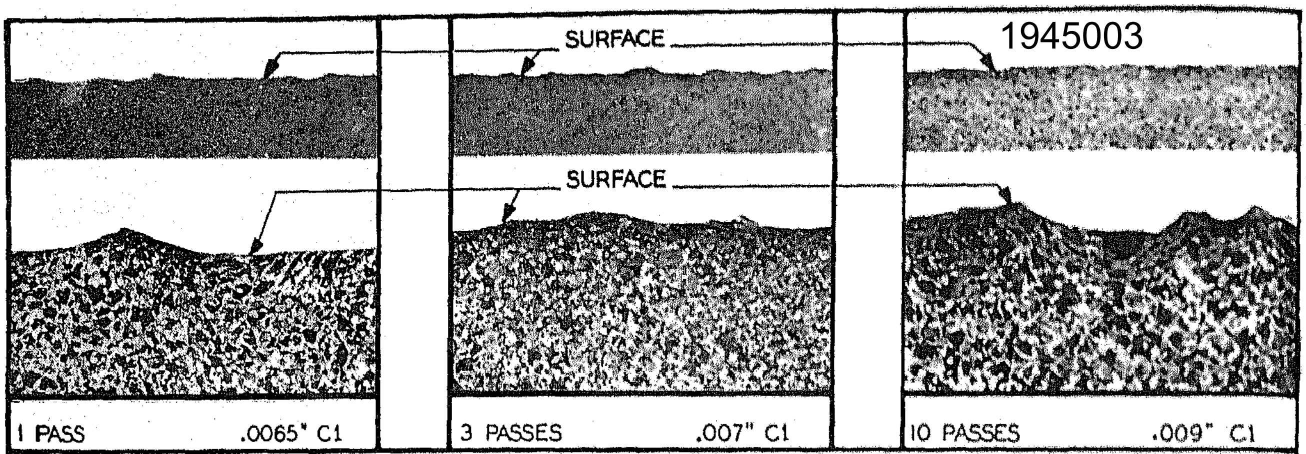
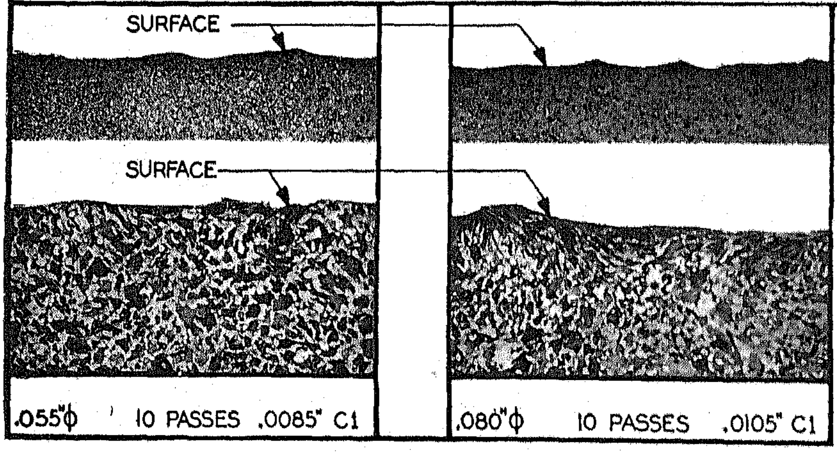


SURFACE CONTOUR (TOP x 30) & MICROSTRUCTURE (BOTTOM x 100) OF FATIGUE SPECIMENS SHOT PEENED BY WHEELABRATOR. SHOT DIA. 0.0315".



SURFACE CONTOUR (TOP x 30) & MICROSTRUCTURE (BOTTOM x 100) OF FATIGUE SPECIMENS SHOT PEENED WITH AIR BLAST.

ABOVE

FIG. 30—Structural conditions at surface of peened SAE 1045 shafts.

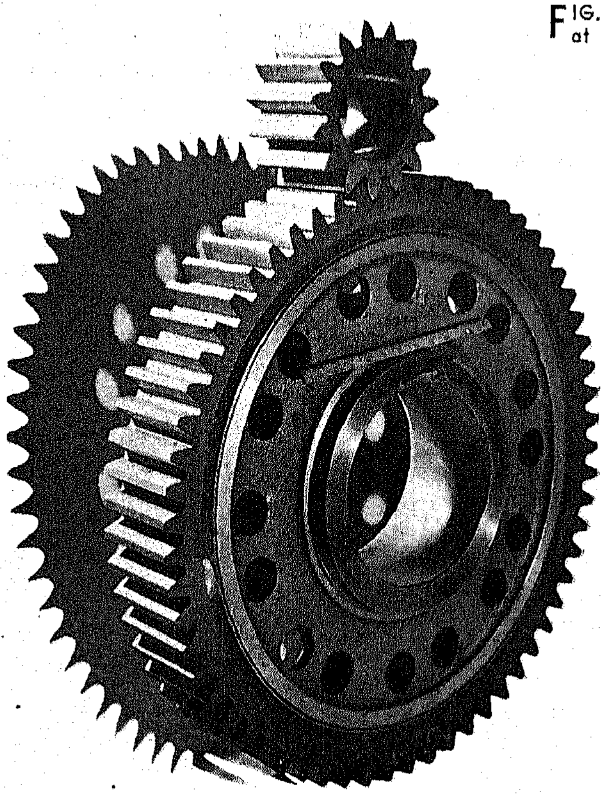


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FIG. 31 — Shot peened gear and pinion. (Simon).

tempered. This curve is based on peening fillets which were only smooth turned and not polished. An endurance limit increase of 54 per cent was obtained by peening as compared with the polished fillet.

Consequence of shot size is also reviewed[23] in Fig. 26. Here the arc height is correlated with endurance limit obtained for filleted shafts. It must be observed that the smaller shot size is more beneficial than the larger sizes but these findings only apply to the conditions investigated. Further data in Fig. 27 show that if the filleted shafts in Fig. 26 are given only one pass under the shot stream then the larger size shot is more beneficial[23]. In Fig. 27 the 1¼-in. diameter plain specimens without fillets stress concentration, however, gave the best endurance with the medium size shot. Other unpublished data exist which indicate that the larger size shot is more beneficial when stress concentration due to shape of the member is present. These above curves are expressive, however, of the fact that all peening conditions on smooth turned filleted or plain shafts gave improved fatigue resistance over those having polished surfaces. Obtaining the optimum endurance requires fatigue tests on the material, design, surface, and blasting conditions concerned with each production part.

A measure of the degree of cold work accomplished by peening is the

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arc height but it is apparent from Figs. 26 and 27 that there is poor correlation of arc height with endurance. Additional unpublished data confirm this lack of correlation but further data on this question are desirable.

Lupfert[20] also found smaller size shot to give greater endurance than larger shot, as shown in Fig. 28.

That a smooth surface does not necessarily connote the most favorable endurance is obvious from Figs. 29 and 30. These studies all pertain to the surface conditions found on the filleted and plain shafts reported in Figs. 25, 26 and 27.

Peening of Tank Gears

Simon[24] shot peened gears in Fig. 31, which are part of the electric drive system of railroad diesel locomotives illustrated in Fig. 32. These gears are peened as a last production operation after the teeth were previously finished to dimensional accuracy.

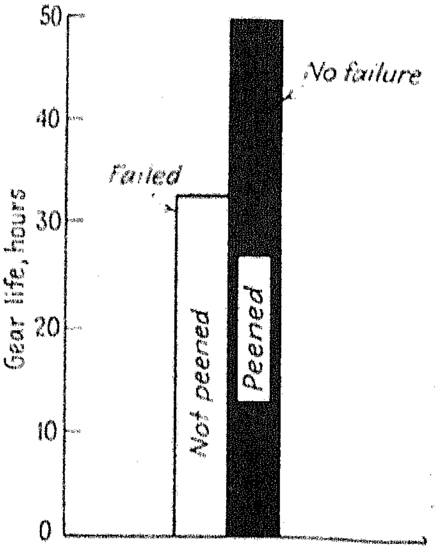
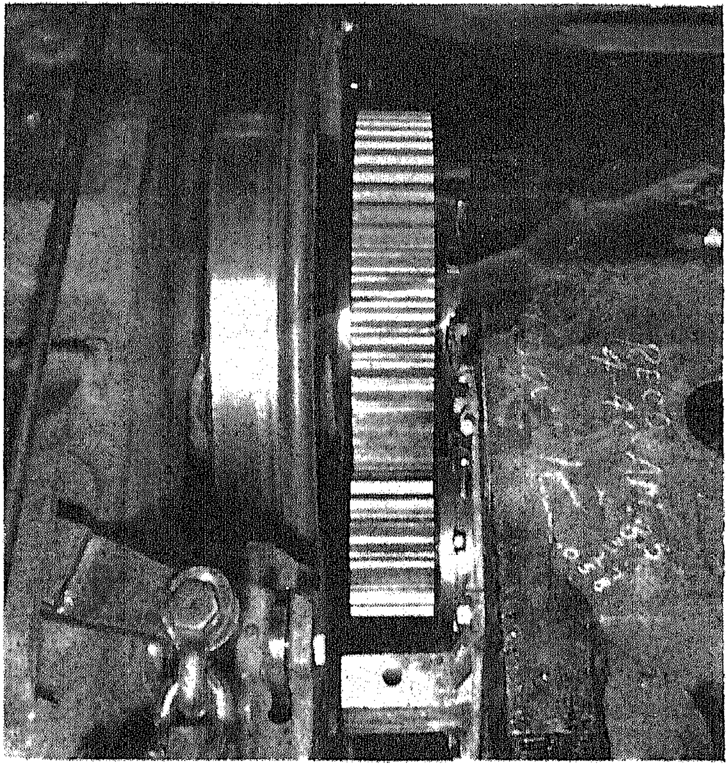


FIG. 33—Idler gear life increased on M4 medium tank from dynamometer tests. (Col. J. H. Frye.)

Some high duty gears have the teeth cut with a protuberance hob and, after shot peening, the mating surfaces on the sides of the teeth are ground. This method leaves the root radius in a peened condition to better resist fatigue fractures.

Some data on increased life of idler gears for M4 tank by shot peening were presented[23] by Frye[4] in Fig. 33. The tests on the peened gears were discontinued after 49½ hr. without

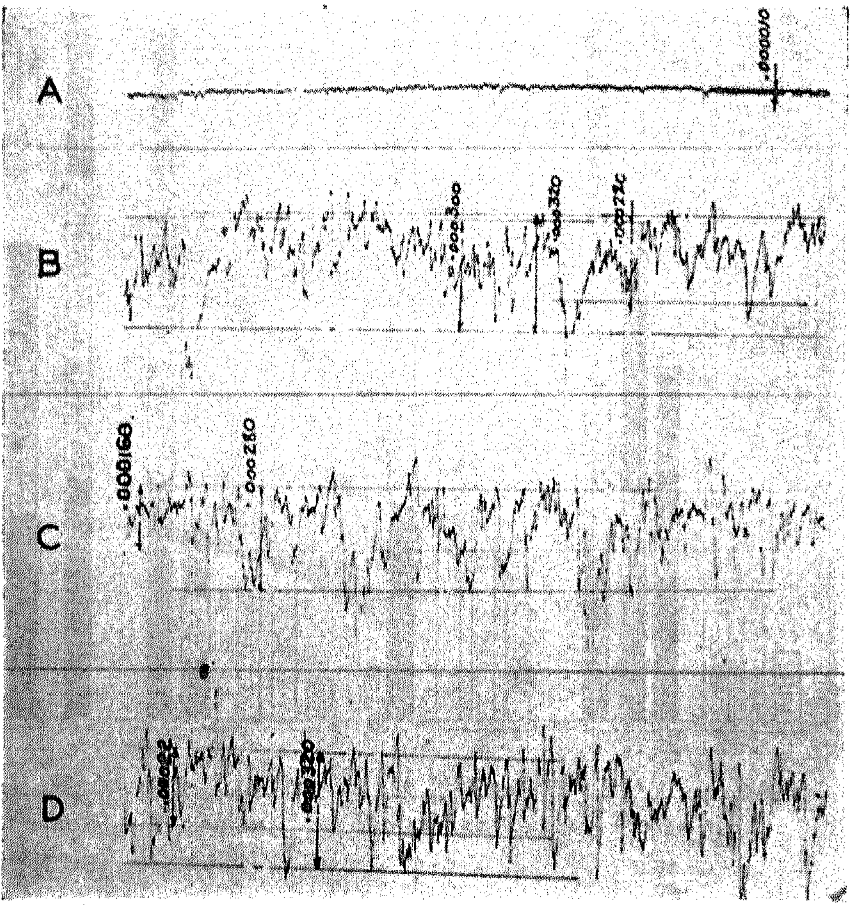


ABOVE

FIG. 32—Diesel locomotive electric motor driving gears are shot peened. (Simon)

BELOW

FIG. 34—Influence of time of blast on surface finish of case carburized parts. (Boden) (A) honed; (B) shot peened 90 sec.; (C) shot peened 5 sec.; (D) shot peened 15 sec. Vertical magnification, 3000 X diameters; horizontal, 30 X diameters; 0.023 in. shot size.



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[4] *Col. J. H. Frye, Ordnance Department, U. S. War Department.*

[5] *E. E. Boden, Experimental Engineer, Timken Roller Bearing Co., Canton, Ohio.*

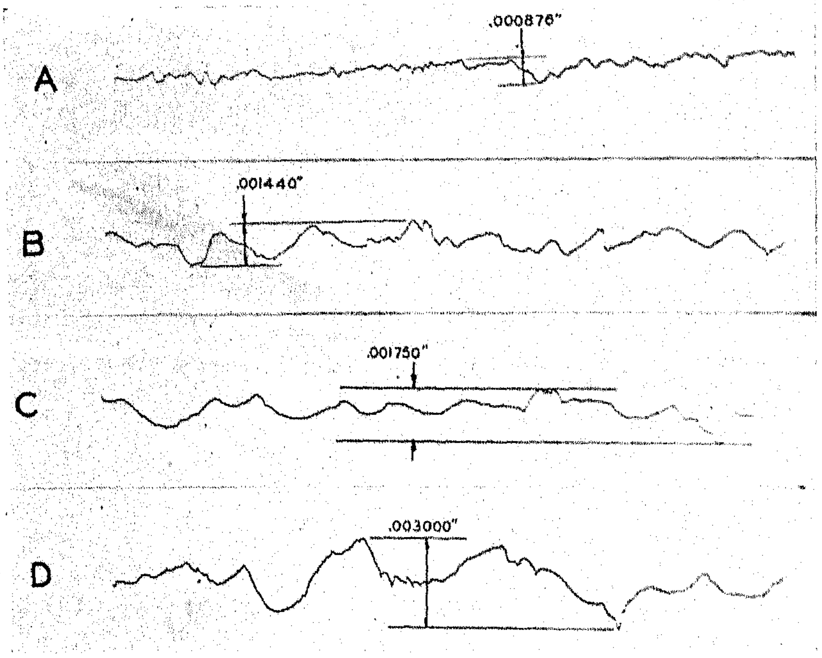
A profilograph was used to obtain all finish records.

failure, whereas non-peened ge failed after 33 hr. Shot size v 1/32 in. with an intensity of 0.16

Boden[7] studied the irregularities surface finish illustrated in Figs. and 35 on case carburized parts whi were shot peened under various c ditions on a Wheelabrator using d ferent sizes of chilled iron shot a with different time under the bla Some design members require certa characteristics as to dimensional a curacy, lubrication, friction, and noi so that a knowledge of these surfa irregularities become necessary.

Improvement of Gun Parts

Valentine[8] presented a clear pictu of how shot peening greatly improv the impact fatigue resistance of ham mers used on automatic guns. His r sults given in Fig. 36 are quoted fro tabular data[9]. Typical hammer fra tures developed in laboratory repeate impact tests are illustrated in Fi 37. Chilled iron shot 0.023 in. t 0.033 in. size was used under 100 l per sq. in. air pressure. The decide improvement in endurance of th hammers by peening NE 8620 wa still further improved by using a sal



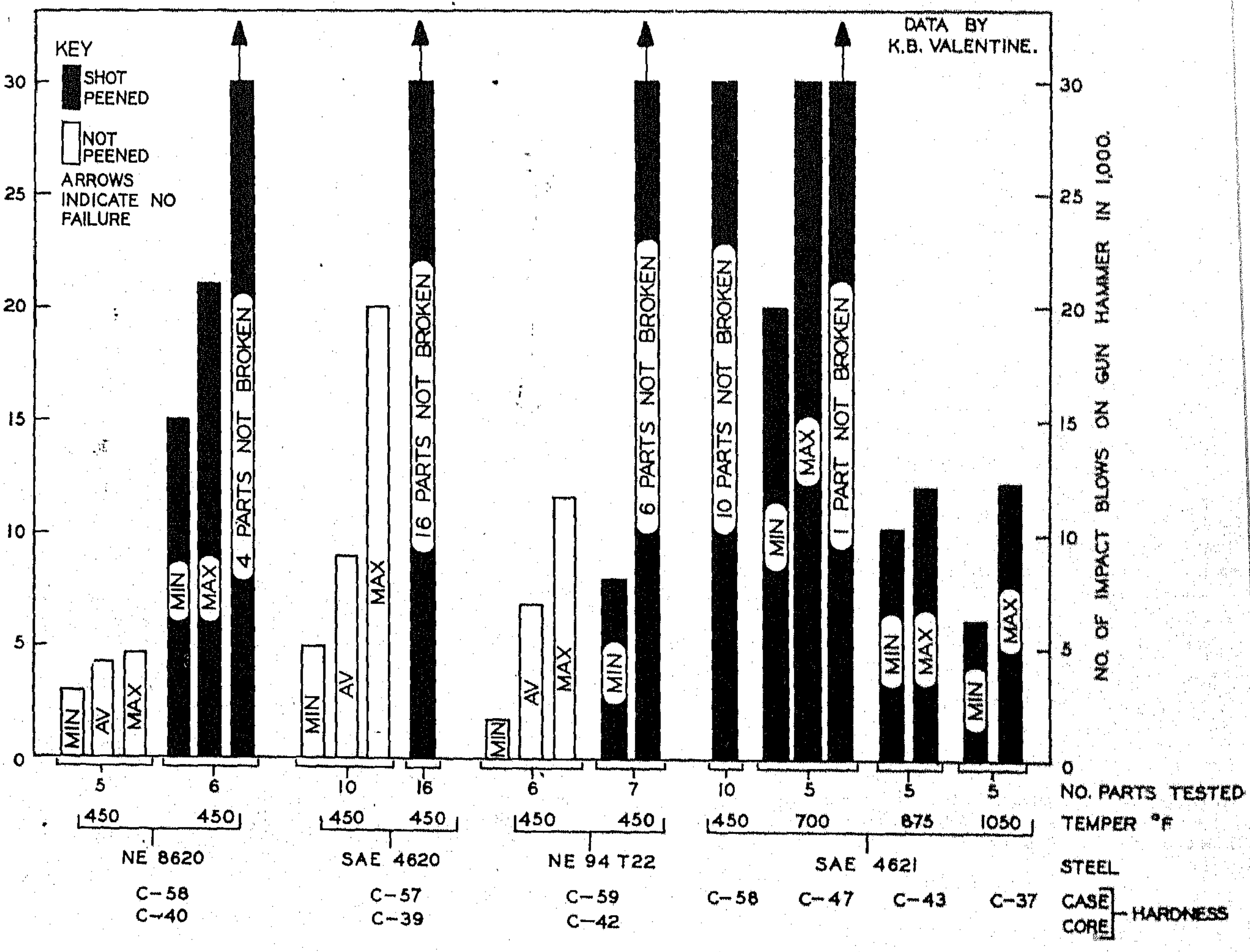
ABOVE

FIG. 35—Influence of different shot size on surface finish of case carburized parts. (Boden). (A) 0.020 in. shot size; (B) 0.033 in. shot size; (C) 0.055 in. shot size: (D) 0.094 in. shot size.

○ ○ ○

BELOW

FIG. 36—Influence of shot peening on the life of case carburized gun hammers subjected to repeated impact loading.



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[8] *K. B. Valentine, assistant chief metal lurgist, Pontiac Motor Division, Genera Motors Corp.*

bath quench at 480 deg. F. followed by shot peening (not shown in Fig. 36). Under this later treatment 15 hammers were tested of which 14 were not cracked after 40,000 impacts and one failed after 24,000 impacts. This case illustrates that the structure previous to peening may be important because Valentine observed that hammers failing at a low number of cycles (NE 8620; salt bath quench 450 deg. F.) had a mixed acicular and brittle structure while those parts which did not fail after 30,000 impacts had small amounts of spheroidal carbides at the surface. The 480 deg. F. salt bath quench was not as critical and produced the desirable spheroidal carbides and resulted in the best endurance values.

Rifle extractors from WD8745 steel were improved by shot peening, as found by Colonel Frye[illegible]. Fig. 38 shows the same test results obtained on extractors under both conditions of (a) Rc 50 surface peened with 0.013 to 0.017-in. shot and intensity of 0.0085A1, and (b) Rc 40 surface peened with 0.019 to 0.024-in. shot and intensity of 0.0138A1. He observed that at lower hardness values it appeared that the endurance life increased with increased intensities, but at higher hardness values the greater intensities tend toward decreased life. This same comment applied to other parts which Frye investigated.

Frye gave further examples[illegible] of improvements in life of gun parts shown in Fig. 39. The extractors were forged from WD4340 steel and surface hardness after heat treatment was Rc 43-48. An intensity of 0.012A2 was obtained with 0.016-in. chilled iron shot. The average life of 1580 rounds on 39 samples not peened was increased to 12,000 rounds by peening.

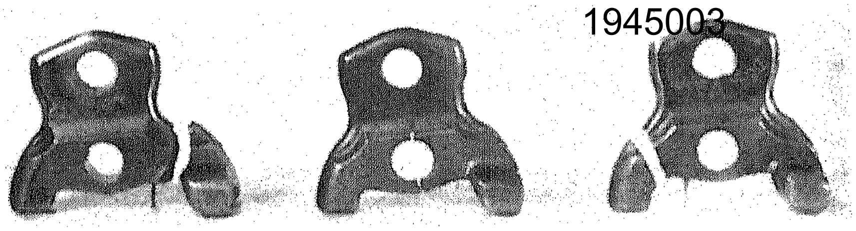

Fig. 37—Typical fatigue fractures of gun hammers. (Valentine.)

On the firing pins he remarked that checking heat treatment and polishing fillet radii resulted in no improvement but peening with 22 mesh shot gave the greatly improved values in Fig. 39.

Peening of Crankshafts

Highly stressed areas of crankshafts are shot peened as shown in Fig. 40. The critical areas are normally the fillets adjoining the ends of the bearings on the main and crank journals. Assuring proper peening conditions in the desired locations is accomplished by the mechanical handling arrangement in Fig. 41. While situations vary it is common to use 0.0248 to 0.0315-in. diameter shot and the crankshaft rotates about its own axis at 50 r.p.m. and the forward travel under the shot stream 2.5 ft. per min. An intensity of cold work equal to 0.020A2 is obtained as measured on the Almen gage. The wheels slinging the shot on the Wheelabrator unit are 19½ in. in diameter by 2½ in. wide rotating at 2250 r.p.m.

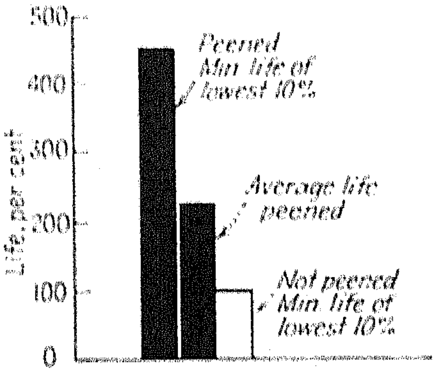

FIG. 38—M1 rifle extractor improved in life. (Col. J. H. Frye).

Studs and Bolts

Studs and bolts subjected to high stresses and particularly repeated impact loading are necked down in the body portion. The engineering value of such design is illustrated in Fig. 42 where Staedel[illegible] reported large increases in repeated impact fatigue resistance resulting from enhanced flexibility. Ordinarily common bolt designs develop fatigue fracture in the threaded portion or under the head but when maximum impact capacity is embodied in the bolt by necking down then failure may place in the reduced body portion. To reduce the danger of such body failure this portion is shot peened. Fig. 43 exhibits bolts and studs which Simon[illegible] peened before the threads are cut. Peening

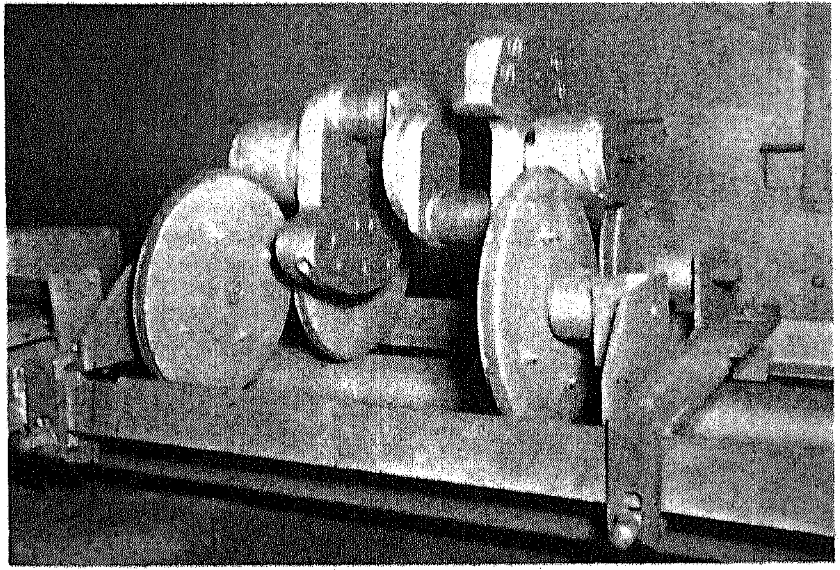

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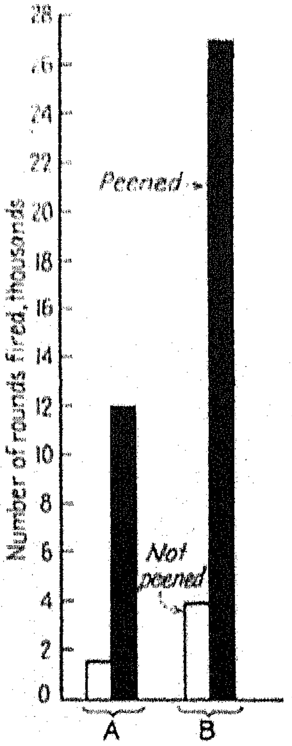
FIG. 39—Average life of gun parts increased by shot peening: (A) Bofors 40 mm. gun extractor, (B) 105 mm. howitzer, M3, firing pin holder. (Col. J. H. Frye).

LEFT

FIG. 40 — Crankshaft in position in shot peening cabinet.



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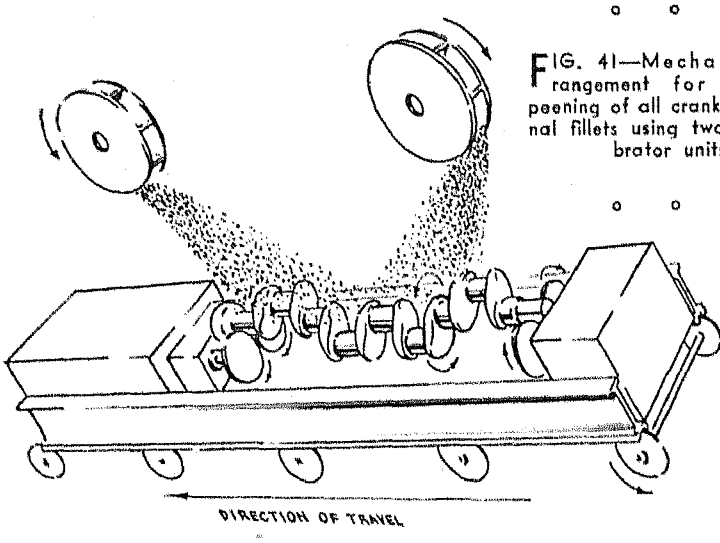
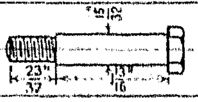
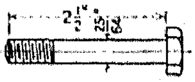
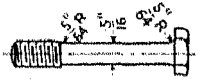
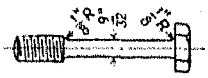
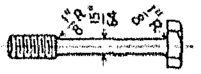


FIG. 41—Mechanical arrangement for insuring peening of all crankshaft journal fillets using two Wheelabrator units.

is applied directly to a machined surface rather than grinding same.

Tank Track Pins

Tank track pins are shot peened in production as shown in Fig. 44. Frye[9] stated that definite and material increase in fatigue life has been obtained by peening. Solid and hollow pins of various alloy steels were investigated using shot size from 0.018 to 0.130 in. and improvement always resulted. Optimum conditions, however, were not revealed. It is not at all surprising to find such improvement because fundamentally this problem involves increasing the fatigue resistance in local regions of fillets and clamped portions where cold working of such surfaces has previously been found beneficial.

BOLT DESIGN	BOLT BODY		BOLT BODY AREA IN % OF AREA AT ROOT OF THREAD	REPEATED IMPACT FATIGUE LIMIT					
				STEEL A		STEEL B		STEEL C	
	DIA, IN.	AREA, SQ. IN.		IN. LB.	%	IN. LB.	%	IN. LB.	%
1 	15/32"	0.175	230	1.73	100	1.73	100		
2 	25/64"	0.122	160	2.60	150	2.26	130	~2.17	100
3 	5/16"	0.076	100	4.34	250	2.78	160	~3.47	160
4 	9/32"	0.060	78	5.21	300	2.95	170	5.21	240
5 	15/64"	0.044	57	6.51	375	3.65	210		

	%C	%Mn	% P	%S	%Si	ULTIMATE (PSI)	YIELD (PSI)	% ELONG.	% RED. AREA	BOLT ULT. *
STEEL A	0.15	0.65	0.095	0.186	0.04	78200		12.8	56.0	93900
STEEL B	0.25	0.75	0.019	0.024	0.25	96400		12.8	54.0	118900
STEEL C	0.33	0.70	0.039	0.027	0.18	85300				
						99600	> 68300	16-10		118000

* Static tensile strength of actual bolt, design 2, having 5/32" length of free threads under nut

FIG. 42—Effect of body diameter of bolt and bolt steel on the repeated impact fatigue strength of bolts. (By Staedel).

Liquid Blast

Very little data of a technical nature have been made available regarding the liquid blast method of surface finishing. By one liquid blast process an abrasive is mixed with a liquid and an agitator type of pump forces this mixture through guns or nozzles in a blast against the part. Grinding marks can be removed from case carburized surfaces by the liquid blast as shown by Boden in Fig. 45. Here a ground surface was prepared by several grinding passes to a final finish of 16-18 micro-in. profilograph reading. A liquid blast containing 1250 mesh abrasive modified this ground surface as illustrated in Fig. 45. That this method actually removes metal in the matter of seconds of exposure from a surface ground

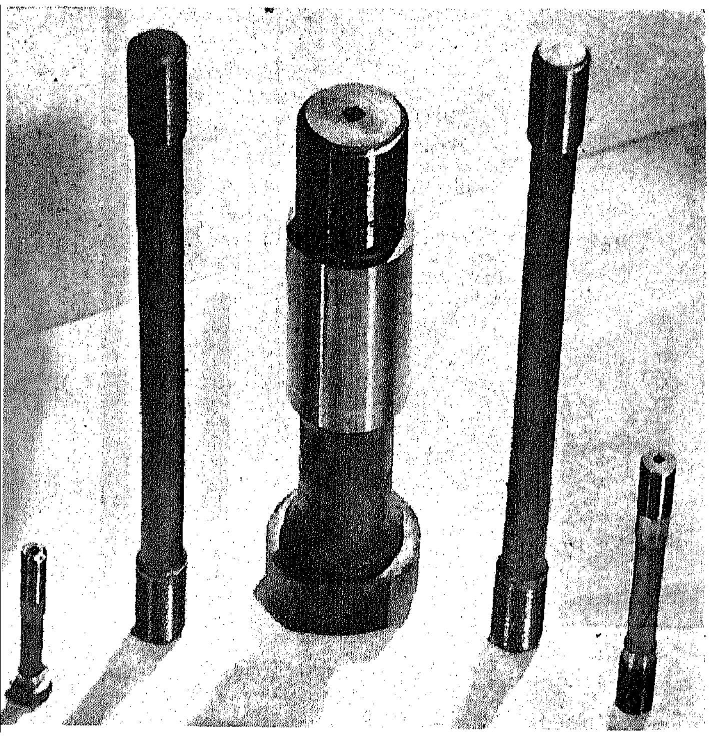


FIG. 43—Bolts and studs shot peened in reduced diameter body portion. (Simon).

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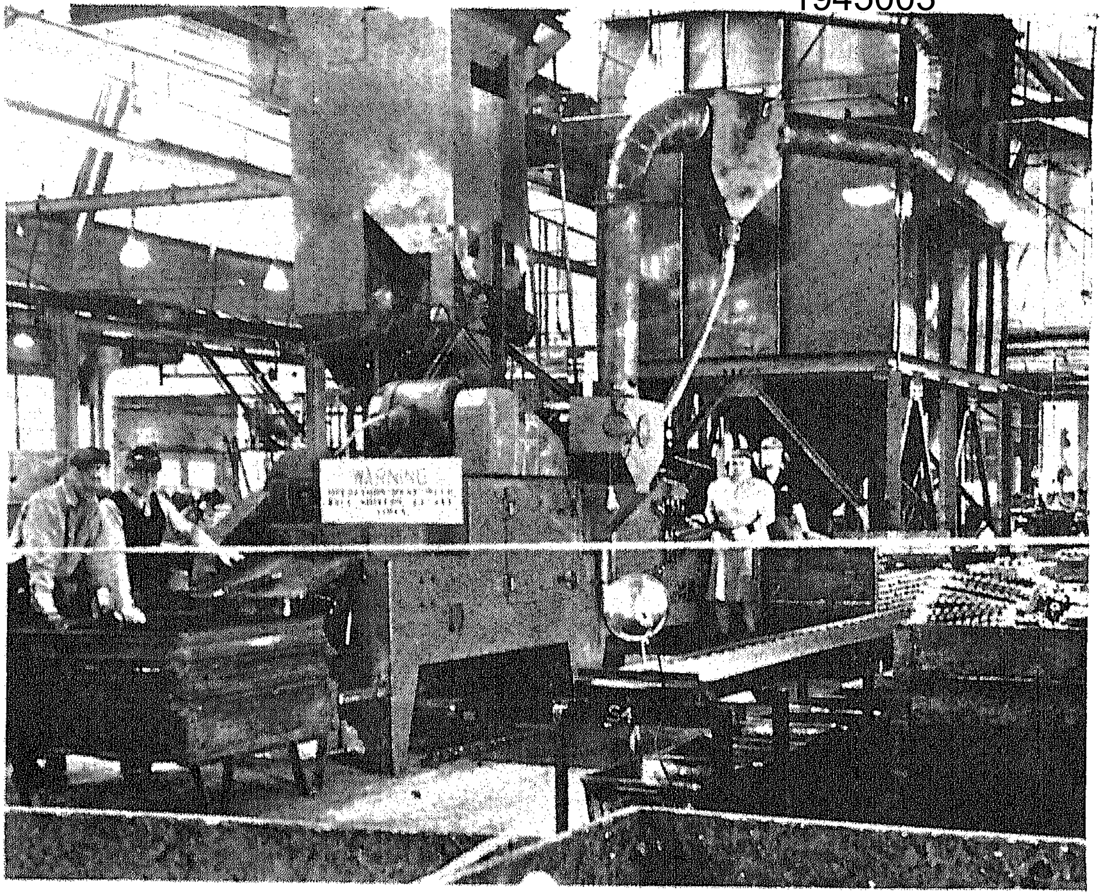


FIG. 44 — Tank track pins shot peened.

after case carburizing is substantiated by the profilograph of the surface finish in Fig. 46. One portion of such a ground surface was masked during the liquid blast and the profilograph trace was made over both finishes. The step in the trace indicates that 180 micro-in. was removed from the ground case carburized surface by the liquid blast.

Outside of the strengthening influence obtained by removing grinding marks and improving surface conditions it is not known what additional contribution to fatigue resistance, if any, would result by the peening effect. Almen strips have shown curvature after blasting but no fatigue data are yet available. In the meantime this process is serving in production lines as a means of surface finishing and warrants investigation as to its influence on fatigue resistance.

Three reasons submitted in explanation for the improved fatigue properties obtained through various surface compression methods such as shot peening or surface rolling are briefly:

(1) Residual compressive stresses are obtained in the surface layers where the applied stresses are usually a maximum and such residual stresses counteract the dangerous tensile stresses arising from operation[8, 11]. The hypothesis[12] for the effectiveness of residual compressive stresses at the surface is that (a) the zero-to-maximum fatigue resistance of steel is greater with compressive loading than with tensile loading, and (b) under the influence of external forces occuring in operation a non-uniform stress distribution arises.

(2) Physical and metallurgical properties of the surface skin are altered by which the surface layer may be densified, grain structure

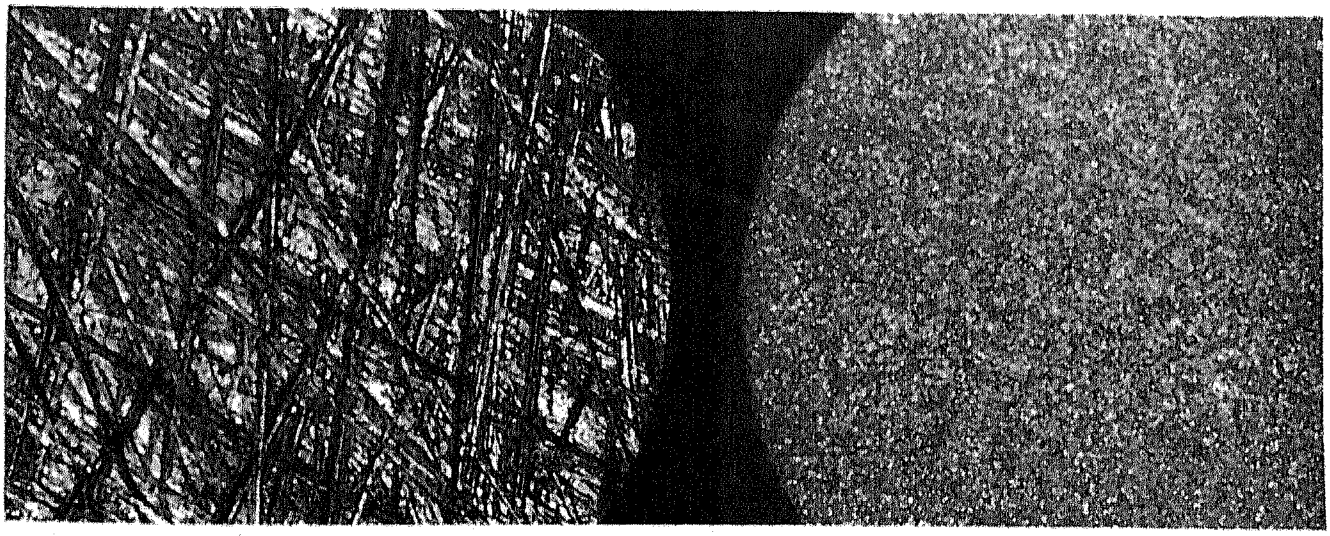


FIG. 45—Surface conditions on case carburized surface before and after liquid blasting, at 100 diameters. Left, multi-pass ground surface; right, after liquid blasting. (Boden.)

changed, damping capacity influenced, elastic limit and notch sensitivity decreased[7, 43, 44, 45, 46].

(3) The free grain boundaries protruding to the surface of a design member are more vulnerable to fatigue failure than grains below the surface. It is conceivable that at and near the surface, where yielding and fracture by fatigue will be initiated, the crystal grains are less constrained by grain boundaries than those situated farther away[47]. While crystal aggregates are considered as isotropic, it is probable that the properties are not uniform in all directions. Surface compression may improve this nonuniformity of properties and the specific elastic shear strain energy (criterion often considered for mechanism of failure) for the surface grains may approach the higher values possibly characteristic of the grains within the body[47]. This is worthy of note particularly on decarburized surfaces when there is a hint of sub-microscopic loosening of the structure[19].

It should be stated at the outset that no investigator has yet submitted factual evidence which would permit positive conclusions as to which one of the three above reasons is responsible. In fact there is better evidence to suggest the possibility of at least the first two arguments acting jointly to give beneficial increases in fatigue resistance. In some cases all three arguments may apply or any combination of the three. It should not be mistaken, however, that any difference of opinion exists as to the favorable effect of cold working on fatigue resistance for there is none; but there is no uniformity of opinion as to why fatigue strength is increased. While this question is of academic interest it is believed that a better knowledge of surface compresson would also be of practical importance in controlling, applying, and obtaining optimum fatigue strength and life of design members. Therefore the research results bearing on this question will be presented.

Thum since the early 1930's has credited the first theory regarding residual stresses for the improvement in fatigue resistance. His more formal implications made in 1935 were[44] that as a result of surface cold working the (a) residual compressive stresses reduce the tensile stresses produced by an external load, (b) shear stress is reduced and fatigue failure is usually predicated on some form of shear theory and (c) stress gradient and magnitude of stress peak are decreased so as to reduce the danger of permanent deformation. Thum made fatigue tests to investigate this question and found[44] that (1) four-fifths of the increased fatigue strength in reversed bending was due to residual stresses and one-fifth was due to strain hardening, while (2) increased torsional fatigue strength was all due to strain hardening. These conclusions were based on the results of fatigue tests made on torsion and bending specimens of the type given in Fig. 47. Some of these specimens were prepared in a special manner by first rolling the 0.030-in. radius groove after it was machined in solid bars. Then these bars were bored out so that the remaining residual stresses were negligible and only

(CONTINUED ON PAGE 146)

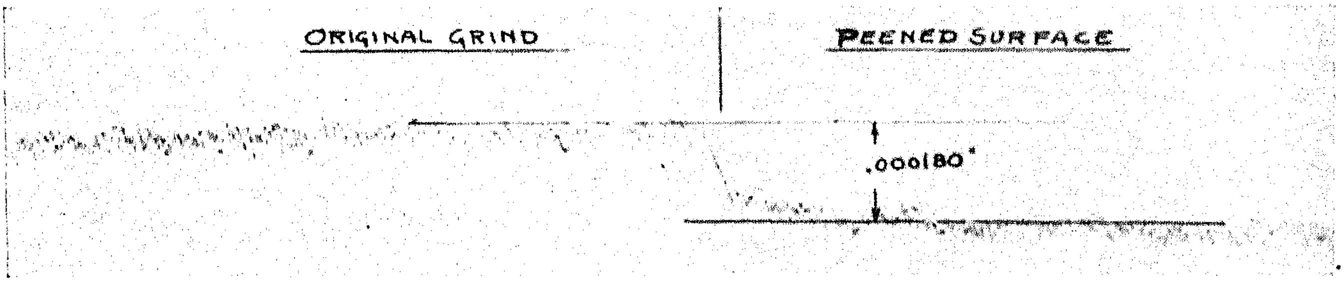


FIG. 46—Profilograph record of case carburized surface indicating removal of 180 micro-in. of metal by liquid blast. Vertical magnification 3000 diameters, horizontal 30 diameters. (Boden.)

FIG. 47—Fatigue specimen used to determine influence of strain hardening and residual stresses. (A) bending specimen, (B) torsion specimen.

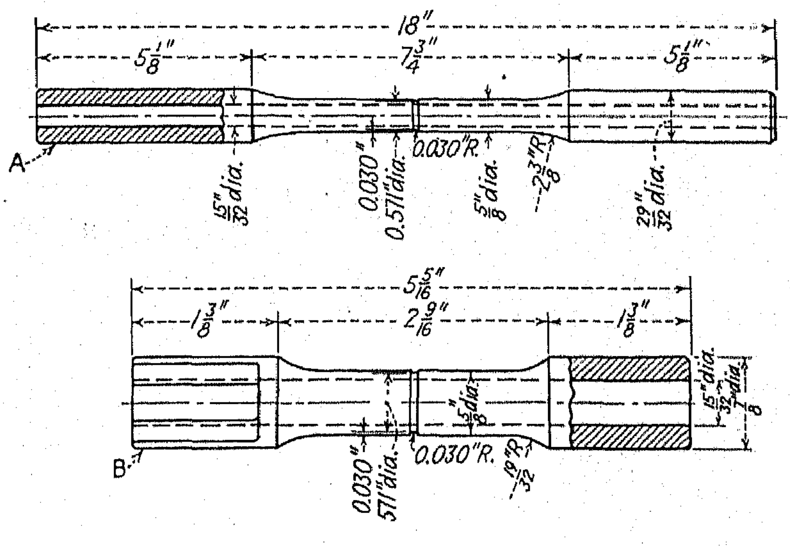
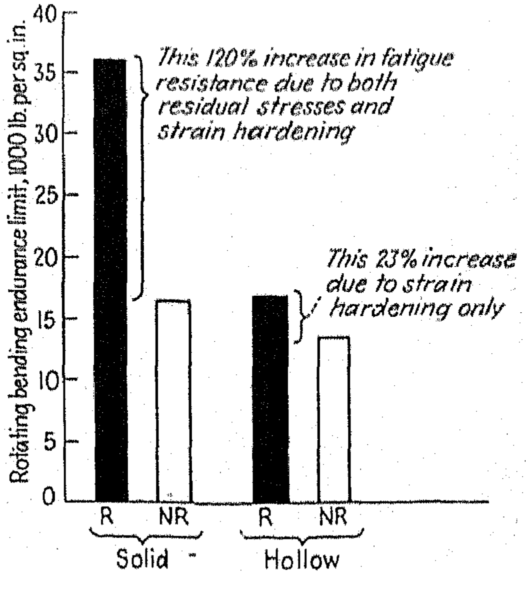


FIG. 48—Bending fatigue resistance influenced by surface rolling; hollow specimen was bored out after rolling. R = rolled and NR = not rolled.



Shot Peening

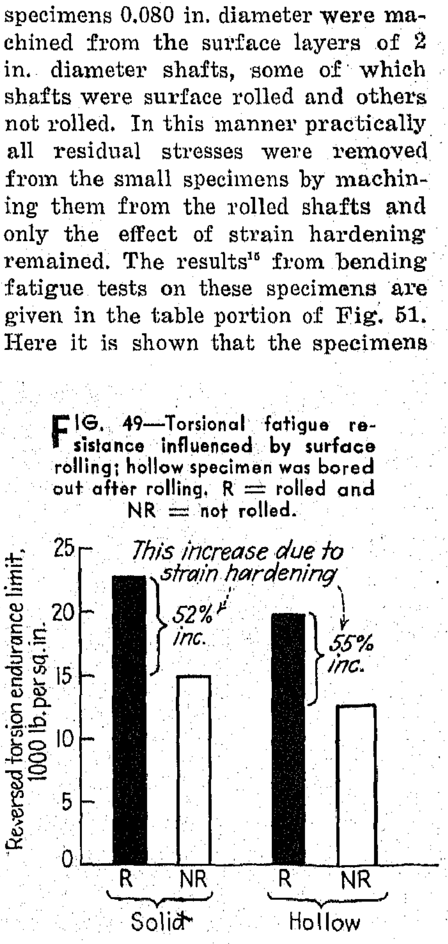
(CONTINUED FROM PAGE 76)

the effects of strain hardening remained. Fatigue results from such solid and hollow bars, which were investigated in both the rolled and not rolled condition, are shown in Fig. 48 for bending and in Fig. 49 for torsion. The basis for his conclusions above is apparent from fatigue results.

Moore and Kommers[48] also developed data on 0.18 per cent C steel and the author[14] on 0.48 per cent C steel, as shown in Fig. 50, which indicated that the presence of strain hardening without residual stresses produced large increases in fatigue resistance. In these tests on two plain carbon steels by independent investigators, steel bars were cold stretched in tension to obtain two degrees of elongation. Then R. R. Moore plain fatigue specimens were machined from these bars. It is apparent that only strain hardening remained in the specimens and residual stresses were negligible so that the latter had no influence on the improved fatigue values shown in Fig. 50.

Again further tests were made which indicated that strain hardening alone without residual stresses gave increased fatigue resistance. Fatigue specimens 0.080 in. diameter were machined from the surface layers of 2 in. diameter shafts, some of which shafts were surface rolled and others not rolled. In this manner practically all residual stresses were removed from the small specimens by machining them from the rolled shafts and only the effect of strain hardening remained. The results[15] from bending fatigue tests on these specimens are given in the table portion of Fig. 51. Here it is shown that the specimens

FIG. 49—Torsional fatigue resistance influenced by surface rolling; hollow specimen was bored out after rolling. R = rolled and NR = not rolled.



from the first layer of the rolled shaft gave 12 per cent greater fatigue resistance than for similarly located specimens from the unrolled shaft. The specimens from the second layer showed an increase of 7 per cent. The table and curve in Fig. 51 also indicate the general relationship between increased hardness and fatigue strength of 1 in. and 2 in. shafts which have been surface rolled. It should be noted that the points plotted for the 0.080 in. specimens fall on the same curve as the 1 in. and 2 in. specimens thereby indicating that strain hardening and not residual stresses may be associated with increased fatigue resistance. Results from the tension strain hardening tests in Fig. 50 are also plotted in a curve in Fig. 51 showing that strain hardening by cold stretching leads to smaller increases in fatigue strength than obtained by surface rolling.

The above examples, and others not mentioned serve to confirm the justification for a more conservative opinion and appraisal of reasons for the favorable fatigue resistance obtained by various methods of surface compression.

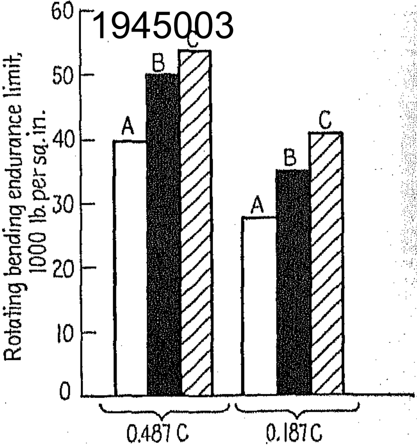


FIG. 50 — Influences of cold stretching on fatigue resistance: (A) no stretch; (B) 8 per cent reduction in area; (C) 17/18 per cent reduction in area.

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