

# The Effect of Shot Peening on Damage Caused by Cavitation

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## SYNOPSIS

Cavitation in a liquid may result from rapid relative motion between the metal and the liquid, for if the pressure accompanying this high velocity drops to the vapor pressure of the liquid, the liquid will vaporize and form a vapor cavity. The collapse of this bubble will cause a concentrated liquid impact resulting in erosion and pitting of the metal surfaces. The designer of hydraulic machinery tries to eliminate this hazard by proper design. In many cases, however, the operating conditions are such that higher efficiency or better economy is attained by operating near cavitation conditions, or even with occasional cavitation present. The task of the designer then becomes in addition to proper design the selection of a suitable material that will be less susceptible to cavitation damage. In the present study the effect of shot peening on the rate of cavitation damage was investigated. Two steels and one brass were tested. It was found that the damage, as measured by the rate of weight loss per unit time, was decreased by shot peening. The amount of decrease varied from 7 to 58 per cent for the different materials.

**C**AVITATION in a liquid may result from rapid relative motion between the metal and the liquid, for if the pressure accompanying this high velocity drops to the vapor pressure—corresponding to the temperature of the liquid—the liquid will vaporize and form a vapor cavity. At a slight increase in pressure this bubble will collapse and will cause a concentrated liquid impact. Thus cavitation is essentially a phenomenon due to instability. This sudden shock loading will cause erosion and pitting of the metal surfaces, and once initiated, it becomes progressive and cumulative.

The designer of hydraulic machinery tries to eliminate this hazard by proper design. In many cases, however, the

operating conditions are such that higher efficiency and better economy are more readily attained by operating near cavitation conditions, or even with occasional cavitation present (1, 2)<sup>2</sup>. It is well worth differentiating between the *micro-mechanism* of cavitation which is a hydrodynamic phenomenon and the resultant macroscopic damage, which is a combination of fatigue, erosion, corrosion, and pitting. This paper deals only with the latter aspect of cavitation.

The purpose of the present study is to investigate whether the effects of cavitation damage could be mitigated by proper surface treatment of the machine parts or elements to be exposed to cavitation. Surface treatment of metals may be roughly divided into two categories: chemical (carburizing, nitriding, plating, anodizing, etc.) and physical (cold working, painting, other mechanical adhesive coverings). The choice of protective surface treatment is natu-

<sup>2</sup> The bold face numbers in parentheses refer to the list of references appended to this paper.

rally a function of the particular design application as well as economic considerations. The beneficial effects of shot peening on the fatigue properties of metals are known (3), but no published reports have been found in the technical literature on the effect of cold working on the damage caused by cavitation. This paper describes a series of tests conducted to study the effects of shot peening on the damage caused by cavitation.

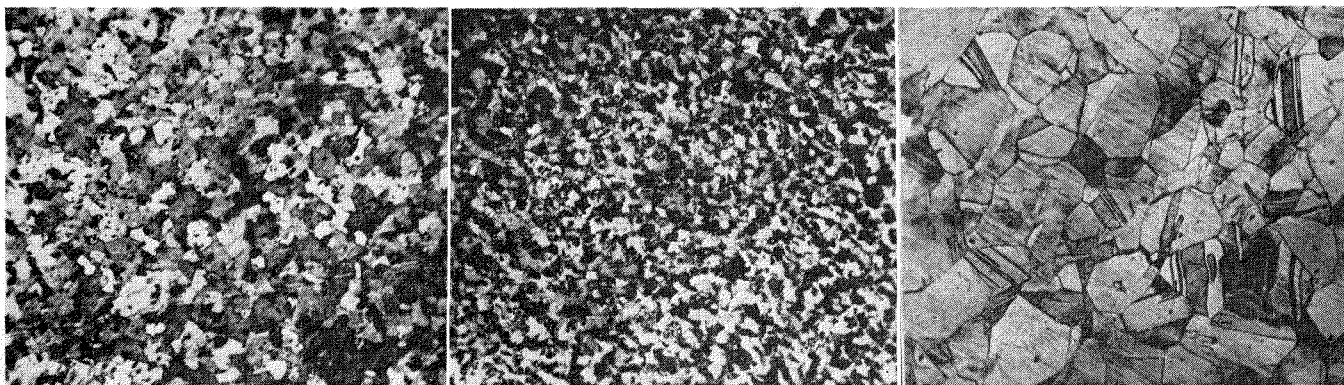
## MATERIALS TESTED

SAE 1020 and 1045 steels and SAE 70C brass were tested. The steels were obtained in  $\frac{3}{4}$ -in. round, hot-rolled bars, fully killed quality. The steels were annealed before the machining of the test specimens. The brass specimens were obtained from a  $\frac{1}{2}$ -in. thick cold-rolled, half-hard plate, tested in the "as-received" condition. Chemical analysis and physical test data are listed in Table I. Representative photomicrographs are shown in Fig. 1. The dimensions of the test specimens are given in Fig. 2. The machined specimens were divided into two batches. One batch received no special surface treatment, and the surface to be exposed to cavitation was finished ground in the surface grinder. The second batch was mounted in a suitable holder and last shot peened. The pertinent data about the shot peening are presented in Table II.

## APPARATUS AND INSTRUMENTS

Several types of laboratory apparatus have been devised by the investigators in order to simulate or duplicate the mechanical effects of cavitation. The

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SAE 1020 steel, annealed; etched in 6 per cent nital. SAE 1045 steel, annealed; etched in 6 per cent nital. SAE 70C brass, as-received; 50 per cent ammonium hydroxide, 50 per cent hydrogen peroxide.

Fig. 1.—Photomicrographs of Materials Tested ( $\times 100$ ).

TABLE I.—CHEMICAL COMPOSITION, PER CENT, AND PHYSICAL TEST DATA OF MATERIALS TESTED.

Material	Carbon	Manganese	Phosphorus	Sulfur	Copper	Tin	Zinc	Lead	Iron	Yield Point, psi	Tensile Strength, psi	Elongation in 8 in., per cent	Vickers Hardness Number
SAE 1020.....	0.21	0.44	0.014	0.033	...	...	...	...	...	41 200	64 100	29.0	114 <sup>a</sup>
SAE 1045.....	0.44	0.79	0.015	0.035	...	...	...	...	...	57 940	95 070	20.0	152 <sup>b</sup>
SAE 70C.....	...	None	...	...	66.51	None	33.36	None	0.03	...	...	...	112

<sup>a</sup> Annealed at 1650 F.  
<sup>b</sup> Annealed at 1550 F.

three basic types are the nozzle, vibrator, and impact.

In the nozzle type the liquid passes through a nozzle where it undergoes an increase in velocity and a corresponding reduction in pressure to below the vapor pressure. This causes the formation of bubbles. The test specimen is mounted at a point downstream where the collapse of the bubbles is taking place.

The vibratory apparatus utilizes the magnetostriction principle. A nickel tube is placed in a high-frequency magnetic field and is caused to oscillate at its natural frequency. The direction of vibration is normal to the face of the specimen.

The impact type of apparatus may be regarded as "simulated" cavitation condition since the impact or pressure waves are produced by a "hydraulic hammer" instead of collapsing bubbles.

The choice of testing apparatus is largely left to the investigator, because a comparison of results shows that there is the same general order of cavitation damage for different materials irrespective of the test method employed (4).

In the present investigation, the vibratory type of apparatus was utilized. The chief advantages of this method are: small, inexpensive specimens; rapidly obtainable effects; good reproducibility. The testing equipment was designed and built at the Institute. In principle it is a nickel tube subjected to magnetostriction by an electromagnetic field tuned to the natural frequency of the tube itself (5). It is made of commercially hard-drawn nickel

total vibrating mass includes, in addition to the nickel tube, a nickel bushing in the lower end and the test specimen which is screwed into this lower bushing.

The principal parts of the setup include the container that holds the liquid in which the specimen is immersed, the supports that hold the nickel tube, the cooling system which maintains the nickel tube at near room temperature, an electronic circuit to produce the high-frequency electromagnetic field, an electric strain gage to measure the amplitude of vibration, and the auxiliary equipment used in the calibration of the instruments. The over-all photograph of the setup is shown in Fig. 3. A schematic diagram of the mechanical parts is given in Fig. 4, while Fig. 5 illustrates the general electronic wiring diagram.<sup>3</sup>

TESTING TECHNIQUE

The container in which the specimen is submerged is filled with distilled water at room temperature. A dummy specimen is vibrated for sufficient length of time to rid the liquid of as much absorbed gas as possible. The specimen to be tested is then cleaned in benzene and acetone, weighed on an analytical balance, and screwed tightly into the nickel tube. The specimen, and part of the tube, are then submerged in the distilled and degassed water, and the tube is caused to vibrate. An SR-4 electric strain gage is fastened onto the tube, and the resulting unbalance due to the rapid extension and contraction of the tube is detected and observed on an oscilloscope tube. (The amplitude of these vibrations can be measured by observing the motion of the specimen with a microscope under stroboscopic light.)

In the present investigation, the frequency and amplitude of vibration were kept constant, and the resultant weight loss measured at regular time intervals. While the data thus obtained may not be directly related to actual cavitation

damage caused under a wide variety of conditions, with different liquids, specimen geometries, and other factors, they do serve as a qualitative measure in evaluating damage and quantitative tool in comparing the selected factors under study.

RESULTS

Three metals—two plain carbon steels, and one brass—were tested to determine the effects of cold working on the resistance to cavitation damage. First a number of trial specimens of each material were tested to determine the suitable time intervals for measuring the resulting weight losses and to establish an optimum total testing time. These trial runs also served as checks on subsequent runs. After running one complete set of tests, a second set for one material was run, as a further check. The results are given in Table III. The plotted curves are shown in Fig. 6. As may be seen from these curves, there is the first stage of damage initiation after which the rate of weight loss appears essentially unchanged. The rate of damage as measured from the slopes of curves in Fig. 6 is given in Table IV. Figure 7 illustrates the physical appearance of the damage.

Several auxiliary measurements were made to gain additional information about the physical aspects of the damage. These are enumerated below.

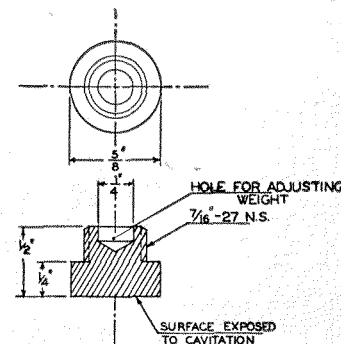
The average Vickers hardness numbers are listed in Table I; a diamond pyramid indenter with a 30-kg load and 1½-in. objective was used.

TABLE II.—SHOT-PEENING DATA.

Shot: S-230 Hard iron chilled—approximately 62 Rockwell C  
 Screen analysis:  
 High limit..... 0 per cent maximum retained on No. 18 screen  
 Nominal limit.. 70 per cent minimum retained on No. 30 screen  
 Low limit..... 20 per cent maximum passing No. 40 screen  
 Test strip: Almen "A" strip—49 Rockwell C  
 Nozzle: ⅜ by ¼ in.; 6 in. from work; Injector type blast  
 Air pressure: 43 psi  
 Impact angle: 90 deg  
 Full saturation: obtained upon sixth pass

about 12 in. long by ⅝ in. outside diameter and 0.028 in. wall thickness. It is supported in the vertical position by a metal ring silver-soldered around the center of gravity of the total mass. The

<sup>3</sup> The main features of the electronic circuit are a tuned amplifier with a driving coil L<sub>1</sub> (see Fig. 5), energized by the output of two UV-204A tubes, connected in push-pull, which are supplied by a power pack with a Variac Transformer for control. In addition to the input from the plate circuit of the tubes, which averages about 2000 v alternating current under normal conditions, this coil is polarized by 110 v direct current. A feedback coil, L<sub>2</sub>, is connected in the grid circuit. The tube itself is the oscillator in resonance with the tank circuit composed of L<sub>1</sub> and C<sub>1</sub> as shown in Fig. 5 (6).



WEIGHT OF SPECIMEN = 130 ± 10 g

Fig. 2.—Dimensions of Cavitation Test Specimen.

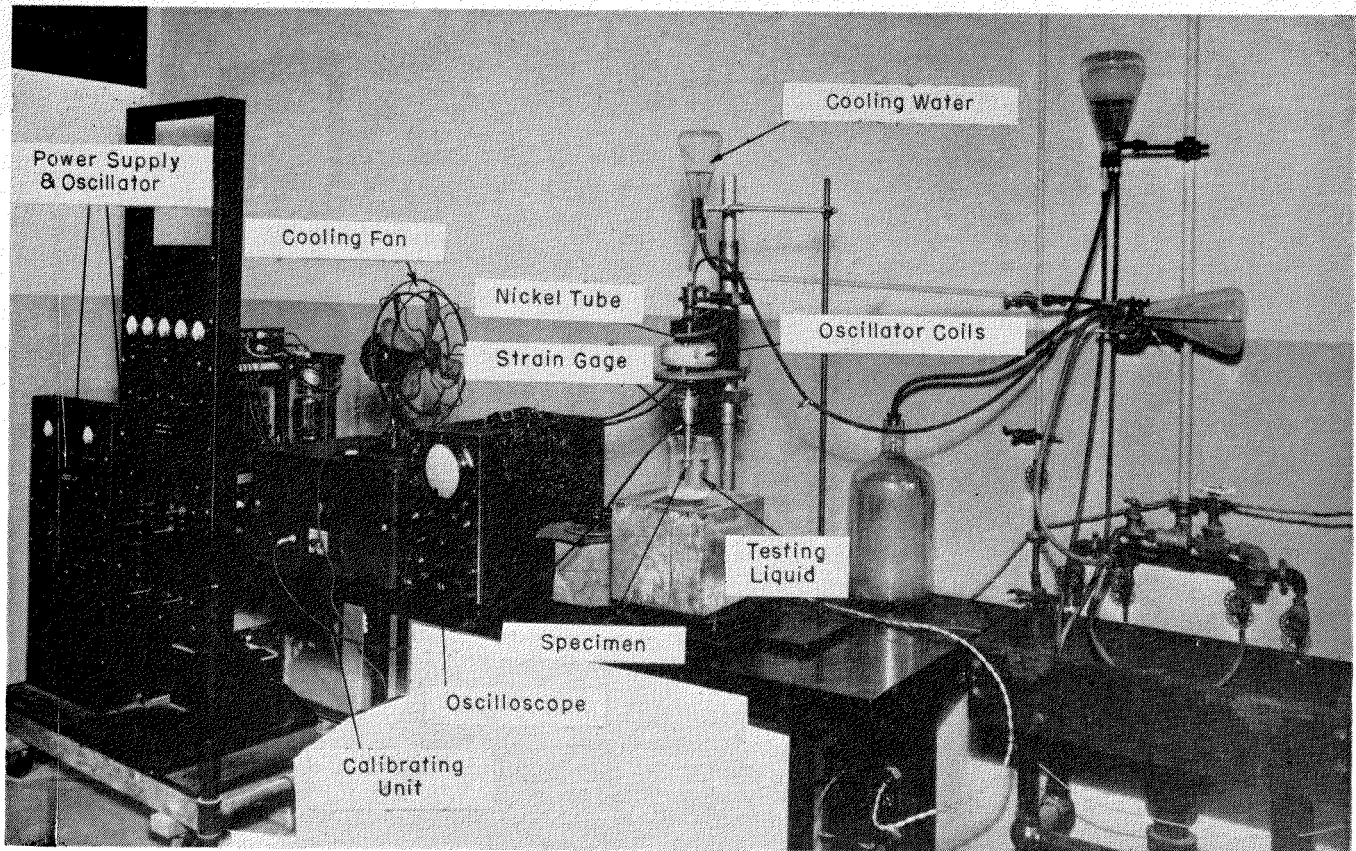


Fig. 3.—Over-all View of Testing Setup.

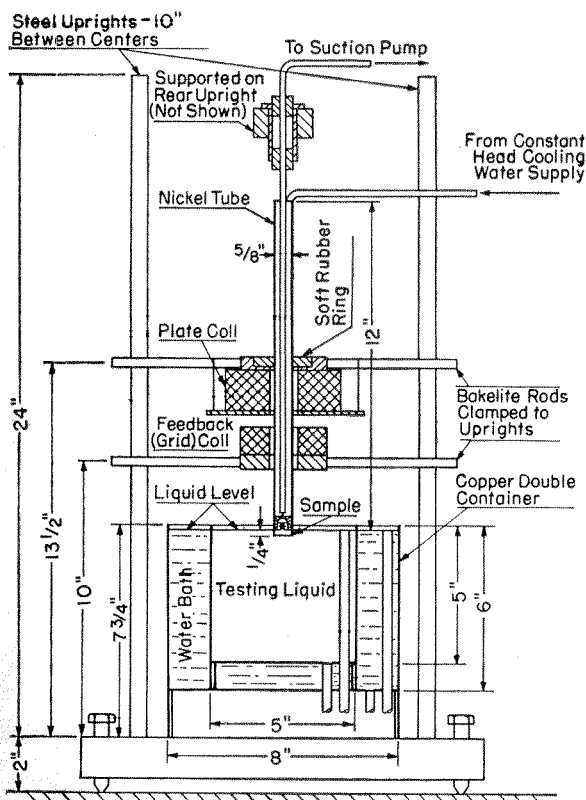


Fig. 4.—Schematic Diagram of Testing Apparatus.

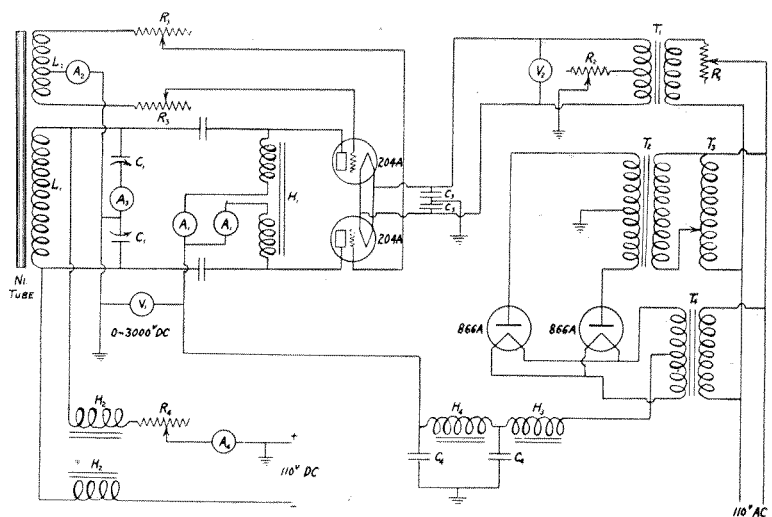


Fig. 5.—Wiring Diagrams for Electronic Circuit.

TABLE III.—RESULTS.

Specimen	Description	Weight Loss, g						
		0	30	60	90	120	150	180
Time Specimens Were Exposed to Cavitation Damage, Min								
No. 3...	1020 annealed	0	0.0019	0.0099	0.0181	0.0248	0.0330	...
No. 2...	1020 shot peened	0	0.0025	0.0068	0.0110	0.0163	0.0209	...
a	No. 15...	0	0.0019	0.0032	0.0060	0.0078	0.0101	0.0123
	No. 12...	0	0.0019	0.0037	0.0057	0.0078	0.0104	0.0124
No. 21...	70C as received	0	0.0033	0.0093	0.0180	0.0274	0.0347	...
No. 26...	70C shot peened	0	0.0024	0.0059	0.0093	0.0131	0.0167	...
a	No. 13...	0	0.0008	0.0022	0.0038	0.0061	0.0094	0.0122
	No. 14...	0	0.0026	0.0040	0.0066	0.0081	0.0104	0.0127

a Average values plotted on curves.

To obtain a relative evaluation of the surface conditions, profilometer readings were taken. A mechanical "Moto-trace" with a total travel of 2 1/8 in. was used to insure uniformity in obtaining the measurements. The average readings for brass are listed in Table V.

To calculate the "pitting factor" the depth of the deepest pit resulting from cavitation was divided by the average penetration as computed from the weight loss. The geometry of the damage was assumed cylindrical, and the average diameter of the base circle was determined from Fig. 7 and taken as 0.30 in. Values of pitting factor are given in Table VI.

DISCUSSION

Cavitation damage of metals is the composite result of repeated, intense shock loads concentrated on minute areas. This mechanical action is supplemented by electrochemical effects, especially in the presence of some corrosive medium. In the present test, the latter effects were minimized by the anaerobic distilled water used for the testing liquid and by the relatively short time of immersion of the metal specimens in the liquid. The only question that may arise is the relative effect of cold working (as introduced by shot peening) on the corrosion of metals. According to previous tests, the effect of cold working on the corrosion of copper and steel in water is insignificant (7). Thus it may be stated that in the present tests the mechanical aspects of cavitation were emphasized and made predominant. Judicious caution should be exercised, however, in applying these laboratory data to engineering field problems, where cavitation conditions

may be quite different from those presented in these controlled tests.

The shot-peened metal layer introduces a highly stressed surface skin which tends to increase fatigue life (3). It also changes the surface roughness; the range of variation of the root-mean-square roughness due to shot peening was about sevenfold (see Table V). In ordinary cyclic tests, the surface conditions of the metal have a paramount significance on the fatigue life. In the present tests, however, the size of the bubbles, the sudden collapse of which causes the repeated shock loading, is unaffected by surface conditions. The intensity (amplitude and frequency) of the vibrations causing the cavitation was kept invariant within the experimental error of the apparatus, as may be confirmed from the resulting damage areas (see Fig. 7). No provisions were

made to control the grain size, and while the comparison of the different metals is used more or less qualitatively, the question arises whether shot-peening, resulting in a distorted metal layer, was not a secondary cause and the differential grain size the primary cause in affecting the damage caused by cavitation. Previous tests conducted to study the effects of grain size on cavitation damage of a single phase metal indicated that the grain size is unimportant (6). It may be concluded that in the present investigation all the attributive factors were either eliminated or kept invariant throughout the tests, isolating the sole factor (that is, shot peening) to be observed and measured.

The mechanism of cavitation damage (in the present experimental setup) seems to have two phases: initiation and propagation of damage. In the first stage the total specimen area to be attacked by the cavitation takes form and the original surface layer is broken down. While the results obtained in this initial stage are just as reproducible as those in secondary stage, the first stage is essentially an unstable phenomenon and it may involve secondary contributory effects. In the evaluation of the test results, therefore, only the second, or steady state of damage propagation should be considered and meas-

TABLE IV.—RATE OF CAVITATION DAMAGE FOR MATERIALS TESTED. (Obtained from Fig. 5.)

Material	Rate of Loss, g per hr	Per cent Decrease in Rate of Loss	Vickers Hardness Number
1020 annealed...	0.0156	..	114
1020 shot peened...	0.091	42	..
1045 annealed...	0.046	..	152
1045 shot peened...	0.043	7	..
70C as received...	0.174	..	112
70C shot peened...	0.074	58	..

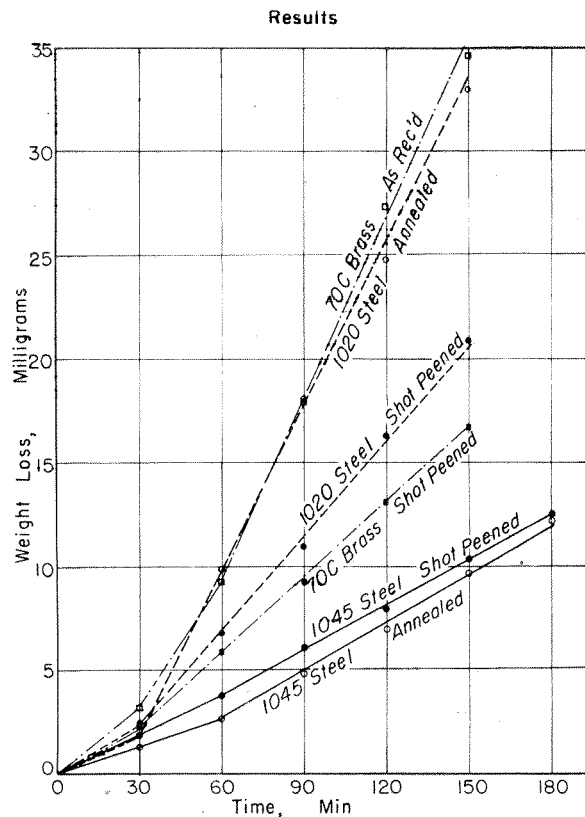


Fig. 6.—Weight Loss - Time Results.

ured. The slopes of the damage lines, plotted as weight loss against time exposed to cavitation, were calculated for the *secondary stage only* (Fig. 5) and listed in Table IV. It may be observed that in all cases *shot peening increased the resistance to cavitation damage* for the specimens tested. The decrease in damage, expressed as a percentage weight loss, varied from 58 per cent for brass to 7 per cent for 0.45 per cent carbon steel. While the total number of specimens as well as the metals studied are insufficient to draw any specific correlation between the decrease in damage and other properties, the relative hardnesses may point toward some explanation. Since shot peening, which is a form of cold-working, introduces a highly stressed and hardened surface layer, the relative workability and resulting hardening—keeping the intensity and length of peening unchanged—will be a function of the original hardness of the metal. In other words the effective-

TABLE VI.—PITTING FACTORS FOR STEEL.

Specimen	Description	Deepest Penetration, in.	Average Penetration Over Damaged Area, in.	Pitting Factor
No. 3 . . . . .	1020 annealed	0.0166 <sup>a</sup>	0.0097	1.7
No. 2 . . . . .	1020 shot peened	0.0176 <sup>a</sup>	0.0062	2.8
No. 13 . . . . .	1045 annealed	0.0115 <sup>b</sup>	0.0036	3.2
No. 14 . . . . .	1045 shot peened	0.0121 <sup>b</sup>	0.0037	3.3

<sup>a</sup> 150 min test duration.  
<sup>b</sup> 180 min test duration.

ness of a given shot-peening operation will be dependent upon the physical properties of the metal to be tested, and if shot peening is to be used to reduce effectively the damage caused by cavitation (the design permitting shot-peened surfaces) the degree of peening has to be established for every metal.

It is noteworthy to observe the deepest penetration in the specimens. As is to be expected, the most intense cavitation takes place around the axis of the vibrating tube and specimen, and while the damage seems to taper off gradually from the center to the periphery there are always a few relatively deep cavities present. After the conclusion of the tests a number of specimens were arbitrarily selected and the deepest penetration measured by determining the height of the specimens as tested, placing them in a surface grinder and removing all but the last trace of damage, and then measuring their

heights again. This deepest penetration was more than 0.01 in. in every specimen thus measured. It is interesting to compare this value with the effective depth of shot peening which was estimated (under comparable conditions) at around 0.006 in. (8). Also notice that the average penetration could also exceed this 0.006-in. deep work-hardened layer (see Table VI) without any noticeable effect on the cavitation damage rate.

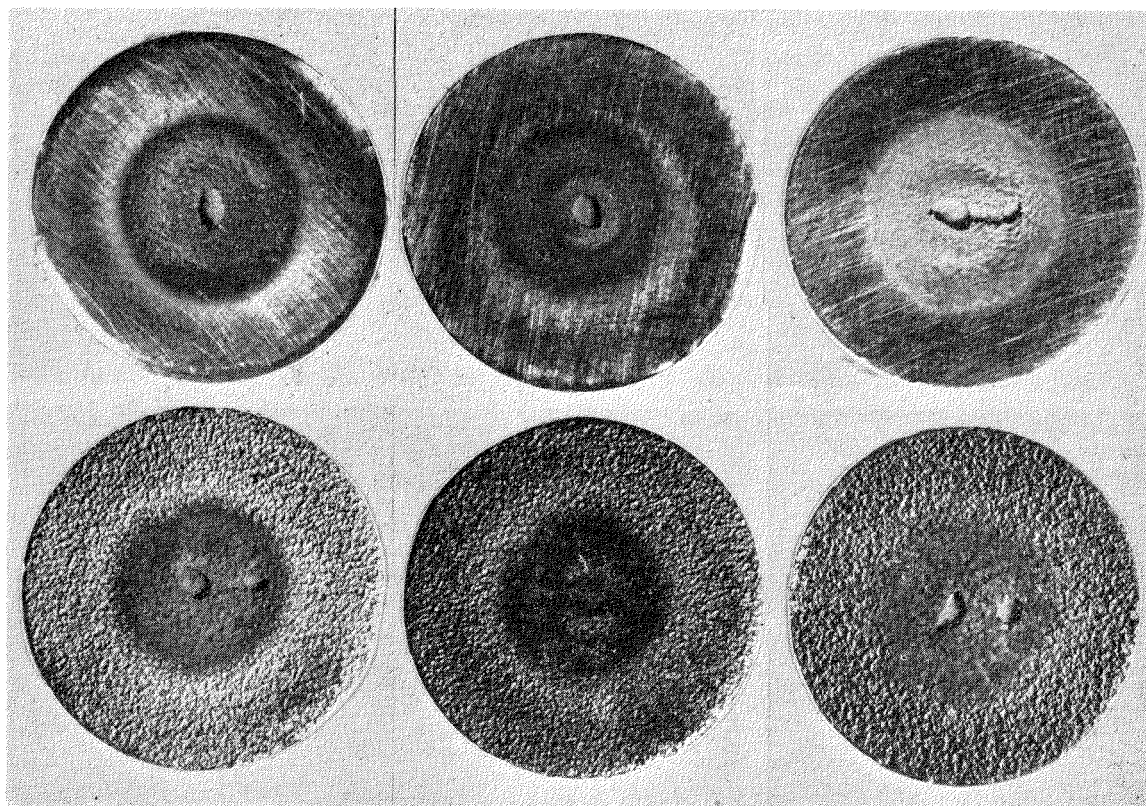
The yield point of SAE 1045 is higher than that of SAE 1020 steel or SAE 70C brass, so that the deformation produced by the impacts is less and there is less opportunity for a breaking of bonds. The rate of damage is therefore lower for SAE 1045. It may be worth while in some future investigation to find a more quantitative correlation between penetration due to cavitation damage and the depth of surface layer affected by shot blasting.

TABLE V.—SURFACE ROUGHNESS MEASUREMENTS FOR BRASS.

	Range of Profilometer Readings, microinch, root-mean square
As received . . . . .	16 to 23
Shot peened . . . . .	18 to 70

No surface treatment.

Shot-peened surfaces.



SAE 1020 steel.

SAE 1045 steel.

SAE 70C brass.

Fig. 7.—Physical Appearance of Cavitation Damage (× 3).

## CONCLUSIONS

It was found that the rate of cavitation damage as measured by weight loss per unit time was decreased by shot peening. The amount of decrease varied from 7 per cent for SAE 1045 steel to 58 per cent for SAE 70C brass.

The effect of shot peening is to raise the yield point of the surface material without breaking any bonds. The greatest improvement is naturally noted for the initial softest materials, provided that they can be work hardened.

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ratory available for these tests. The Pangborn Corp. was most cooperative in shot peening the submitted specimens and supplying the shot-peening data.

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