The Effect of Shot-Peening upon the Corrosion-Fatigue of a High-Carbon Steel

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SYNOPSIS

Steel peened in seven different ways was subjected to corrosion-fatigue in very dilute sulphuric acid and in sea water ; fine-ground unpeened steel was tested for comparison. It was found that peening greatly increased the endurance at stress ranges commonly prevailing in service. The addition of sodium carbonate and sodium bicarbonate to sodium chloride diminished the endurance of peened specimens, probably by localizing the action ; at high alkali contents, peened specimens have a shorter life than finely ground specimens.

Introduction

Nature of the Problem

It has been known for many centuries that the cold hammering of bronze, iron, and steel improves certain of the intrinsic properties of these metals. The process came to be known as " peening." The name was later applied to other treatments which tend to flatten the surface, such as bombardment with round shot. The word should not be applied to roughening treatment, such as that produced by bombardment with similar shot in the broken condition, or with specially prepared grit.

In recent years, shot-peening has completely replaced hammer-peening. Formed from commercial chilled iron, the shot are usually about 0·05-in dia with well-rounded contours ; they are projected on to the work by, (*a*) air-blasting, in which they are carried by means of a high-velocity air stream through a nozzle, or (*b*) airless-blasting, in which they are propelled by a bladed wheel rotating rapidly, and projecting the shot through an aperture. As each shot strikes the surface of the work, it makes a slight indentation ; a residual stress will be left in the metal around and below every point of impact, with the result that a shot-peened surface is left in a state of strain (the system of stresses is internally self-balancing). The situation is, no doubt, complicated when considered in detail, but some authorities think that the result, considered macroscopically, approximates to a state of fluid compression. The condition of the metal is probably fairly uniform at all parts of the surface and may extend downwards into the metal for about 0·01 in.

It is to be expected that such a treatment would improve the fatigue resistance of many machine and structural parts. From experimental evidence, the tensile half-cycle of an alternating fatigue stress does more fatigue damage than the compressional half-cycle. Consequently, the residual compression in a shot-peened surface should reduce the severity of the tensile half-cycle in the case of any component in which the fatigue stress is a maximum at the skin, such as a rotating beam, or a vibrating bar.

Actual experiments indicate that shot-peening does greatly prolong the life of parts subjected to fatigue. Generalization is difficult, but cases are on record where working lives have been improved up to twenty or more times for particular machine parts.[1, 2] Such a marked improvement cannot be expected, however, where the components are under push-pull stressing. In such a case the stress distribution is uniform over a cross-section, and a fatigue nucleus could appear anywhere in the whole volume of stressed metal, and not necessarily close to the surface. Skin imperfections certainly exist, and perhaps exert weakening influences slightly exceeding those due to chance internal imperfections. It follows that shot-peening may be expected to improve only slightly the fatigue properties of highly polished components under push-pull stresses ; where components are left with rough surfaces, peening should improve the endurance to fatigue of this kind to a greater extent.

In the case of corrosion-fatigue, destruction always starts from the surface of a stressed part. Attack by the conjoint chemical and mechanical action causes narrow fissures, which grow inwards from the surface of the metal until they become cracks. From their nature, the residual compressions left by shot-peening must surely delay the inception of corrosion-fatigue fissures, and perhaps even for a time their extension after their initiation ; firstly, by diminishing the virtual effect of the tensile half-cycle of fatigue stressing, and secondly, by closing any incipient surface cracks, which would otherwise constitute stress-raisers, and also provide places favourable to corrosion.

Consequently, it is to be expected that shot-peening will improve the corrosion-fatigue resistance of any metal component, irrespective of the kind of fatigue stress which operates.

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The Plan of the Present Research

The research was undertaken to investigate the corrosion-fatigue properties of peened test-bars manufactured from a single cast of steel. Some bars were kept in the "as-ground" condition for testing as controls ; the rest were peened. Seven kinds of peening treatment were employed.

Experiments were conducted with the following corrosive liquids :

(*a*) Aerated 0·005 normal H_2SO_4, a concentration which was thought to exceed the acidity of the condensate (dew) deposited in the evening on steel surfaces exposed to industrial atmospheres
(*b*) Aerated sea water
(*c*) Aerated 0·5 normal NaCl containing different concentrations of an equimolecular mixture of sodium carbonate and sodium bicarbonate.

Specimens were tested under reversed stress on a rotating machine fed with corrosive liquid, until fracture occurred. The data were expressed as stress-endurance (S–N) curves, which provide a rapid assessment of the effects of different kinds of peening.

EXPERIMENTAL SECTION

The steel used was supplied by Rylands Bros., Ltd., Warrington, through the kindness of Mr. R. S. Brown, and had the following chemical composition :

C, %	Si, %	S, %	P, %	Mn, %
0·80	0·17	0·039	0·024	0·57

The steel was rolled to 2-in billets, reheated, and again rolled, then pickled in HCl, limed, and drawn unpatented to 0·5 in. The rods were patented by heating to 1030° C, and cooled through lead at 502° C, the process being continuous. The stock was then drawn, in two passes on a rack bench, to the required size of 0·375 in. It was straightened and polished by reeling. During reeling the diameter increased by 0·004 in, and each length was ground to remove this excess. Finally the material was cut into test-bars 12 in long ; these were finished by centreless grinding to 0·360 ± 0·001-in dia. The final operation produced an exceedingly good surface finish.

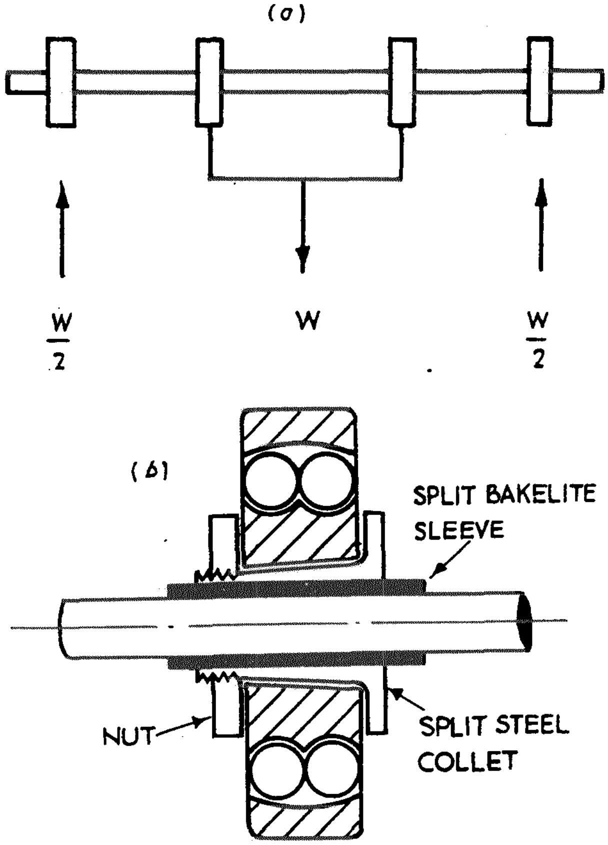

Fig. 1—(*a*) Arrangement for four-point loading in fatigue-testing machine; (*b*) Method of securing ball bearing

One third of the ground bars were preserved for testing as controls. The rest were peened, according to standard practice, by Messrs. J. W. Jackman and Co., Manchester, through arrangements made by Mr. W. E. Ballard and Mr. F. W. Neville. Only the central three inches of each bar received peening.

The conditions of peening were :

Nozzle :	2·5 in × 0·125 in, slightly divergent to cover a length of 3 in at a distance of 6 in from the nozzle tip
Time of treatment :	5·2 sec per bar
Air pressure :	As stated below
Shot sizes :	*Large*—passing mesh $\frac{1}{21}$-in square opening, not passing mesh $\frac{1}{38}$-in square opening *Small*—passing mesh $\frac{1}{38}$-in square opening, not passing mesh $\frac{1}{50}$-in square opening
Grit sizes :	*Large*—commercial grade D *Small*—commercial grade E

Seven types of peening were used, shown as follows :

Group	Air Pressure, lb/sq.in.	Type of Peening Treatment
1	30	With large shot
2A	30	With large shot, followed by treatment with small grit for 5·2 sec.
3	30	With small shot
4	40	,, ,, ,,
5	50	,, ,, ,,
6	30	,, large grit
7	30	,, small grit

In Group 2A it was hoped to produce a surface retaining the advantages of peening but sufficiently rough to provide good adhesion when a sprayed metal coating was subsequently applied.

The chemical solutions were made up from B.P. reagents and distilled water. The sea water, taken from Chichester Harbour, was supplied by Dr. Slater.

Tensile tests were conducted upon bars of unpeened material, 0·20-in dia, and furnished the following mean values :

Ultimate tensile stress, tons/sq.in.	90·5
Elongation on 2 in, %	5
Reduction in area, %	36

No yield could be detected during the tests.

Apparatus

The machines used for corrosion-fatigue testing were of the rotating-beam type. They were similar to those used previously in the laboratory by Huddle,[3] modified in detail to reduce torsional oscillation. Four-point loading was provided through four ball

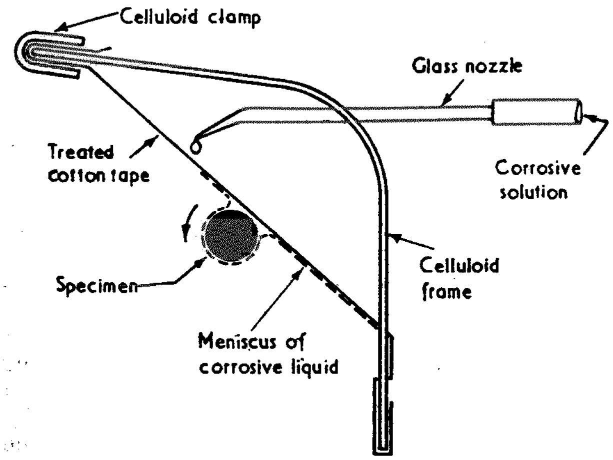

Fig. 2—Arrangement for applying corrosive liquid

bearings which firmly engaged the specimen by means of inserted split-collets and split bakelite sleeves, as shown in Fig. 1.

The test-bars were of parallel section, 12-in long and 0·360-in dia. Before a test, the middle portion of the specimen was carefully degreased by means of repeated swabbings, first with benzene, then with carbon tetrachloride, and finally with acetone.

The corrosive solutions, previously shaken with air, were carried in a reservoir above the apparatus, and were allowed to drip upon a cotton-tape sling[3, 4] which served the corrosive to the specimen as shown in Fig. 2.

Method

Specimens were placed in the machine and then rotated at 1500 r.p.m. The load was then applied, the corrosive solution served, and the revolution counter started. Each test was continued until the specimen broke, when the machine was stopped automatically. The counter reading gave the endurance of the specimen at the particular stress employed.

Results

The main results were expressed in the form of stress-endurance curves:

(*a*) Showing the fatigue properties of uncorroded and unpeened steel
(*b*) Comparing the behaviour of the steel in various peened and unpeened surface conditions, when subjected to corrosion-fatigue in dilute acid
(*c*) Comparing the behaviour when subjected to corrosion-fatigue in sea water.

In those experiments designed to test the effect of adding sodium carbonate and sodium bicarbonate, curves were plotted showing the relation of the endurance numbers to the concentration of the added salts.

The alkaline buffer solution (X.M. Na_2CO_3 + X.M. $NaHCO_3$) was used at a number of different concentrations varying from $X = 0$ to $X = 0 \cdot 7$; the upper limit of X was imposed by the limited solubility of $NaHCO_3$.

The air-fatigue properties of the steel, very finely ground with a sequence of emery papers ending with 0000 and then covered with unmedicated vaseline, are indicated in Figs. 3 and 4. Recorded there also are the results obtained in 0·005 N sulphuric acid and sea water respectively. Control specimens, with the surface "as-ground" (not peened), are included in the figures.

Figures 3 and 4 may be considered together. They indicate that peening causes a marked improvement of endurance at reasonable working stresses, under the specific conditions of testing used. Some types of peening were found to be very much better than others.

The results obtained in M/2 NaCl made alkaline with sodium carbonate/sodium bicarbonate buffer are shown in Fig. 5. It will be observed that whatever the concentration of the buffer, the peened bars always had a greater endurance than unpeened bars in the unbuffered solution. On the other hand, at high alkali concentrations, the peened specimens had shorter lives than unpeened specimens exposed to the same solution; thus peening does not always bring about an improvement.

DISCUSSION

Preliminary Remarks

Before a critical consideration of the results is attempted, the following remarks are offered:

(*a*) The steel adopted for this work had an unusually large carbon content, approximating to that of a spring steel. It could not be regarded as typical of steel used for general engineering purposes. When the work was started, it was the only metal of high quality readily available for the production of the specimens.

(*b*) The test-bars were ground to a parallel section without any reduction of diameter in the middle: it was the only machining possible at the time. In consequence, heavy stress-loading of the test-bars caused severe frettage-corrosion at the sleeves of the middle bearings in the machines. Breakage often occurred at these points, so that values of the endurance at high stresses were difficult to obtain. By the use of bakelite sleeves and a lubricant of zinc oxide in vaseline, some values were secured, but only after a considerable wastage of specimens. The difficulty was more pronounced with sea water than with weak acid, because of lateral creepage.

(*c*) The experiments had to be conducted in an open laboratory because a thermostated room was

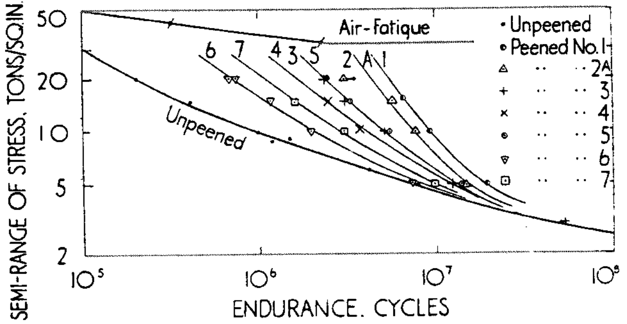

Fig. 3—Stress-endurance curves for specimens subjected to corrosion fatigue in dilute sulphuric acid

not available. However, thermometer readings were recorded and averaged during every experiment, and a temperature correction was applied to each endurance so that standardized values could be plotted. The factor used, namely a 3·3% increase of endurance per degree F fall of temperature, was obtained from previous work.[5] The corrected results fell on curves in a satisfactory manner, whereas the uncorrected ones were badly scattered.

(*d*) The peening was conducted upon test-bars which had been accurately machined and highly finished. In practice, this procedure would be considered unnecessary and expensive, since a rough finishing could be used without disadvantage, but it is not absolutely certain that the same benefits would be obtained from peening a rough surface.

Interpretation of Results

That a peened surface suffers less damage under corrosion-fatigue conditions than a fine-ground surface in acid or neutral solution, is not surprising. Damage due to dry fatigue is diminished by peening, probably for two reasons; the process closes up any submicroscopic fissures which would form the most favourable starting-places of fatigue cracks, and the residual stresses, being additive to the applied stress, tend to diminish the resultant stress during the dangerous tensional half-cycle, although increasing it on the less dangerous compressional half-cycle. Thus it can be understood that the transformation of the saucer-shaped cavities, characteristic of stressless corrosion, into the cracks characteristic of corrosion fatigue—a development studied by McAdam and Geil,[6] and later at Cambridge by Simnad[7]—will occur less readily and less rapidly on a peened, than on an unpeened, surface.

Up to a point, the improvement might be expected to increase with the momentum of the shot-particles. The curves corresponding to steel peened with small shot at 30, 40, and 50 lb/sq.in. respectively show that the lives increase with the momentum in sea water (Fig. 4), but that in acid (Fig. 3), the steel specimens peened at 40 lb/sq.in. have consistently shorter lives than those peened at 30 and 50 lb/sq.in.; this is not easy to explain.

Another strange result is that in solutions of sodium chloride containing relatively large amounts of alkali (Fig. 5), peened steels have shorter lives than unpeened. This is of great practical importance, since saline waters which have been treated with alkali with a view to preventing stressless corrosion must be regarded as likely to produce corrosion-fatigue more readily on a peened than on an unpeened surface.

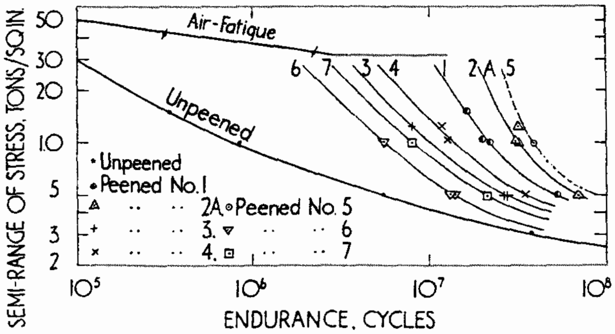

Fig. 4—Stress-endurance curves for specimens subjected to corrosion-fatigue in sea water

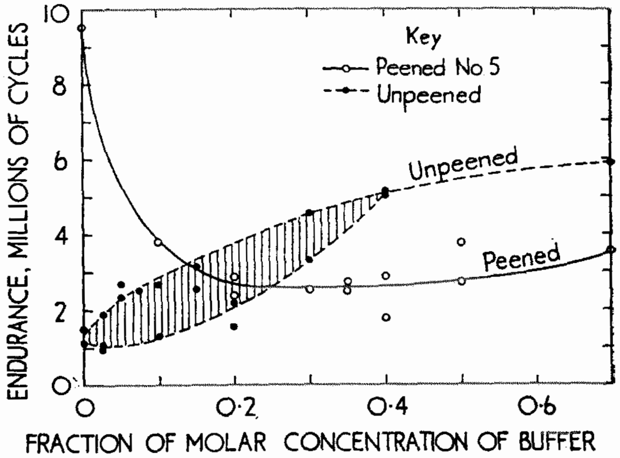

Fig. 5—Endurance curves (at ± 10 tons/sq.in.) for specimens subjected to corrosion-fatigue in sodium carbonate/sodium bicarbonate buffer solution of different concentrations

An explanation may be tentatively suggested. The addition of alkali in small amounts to sodium chloride is known to diminish the corroded *area* more quickly than it diminishes the *total attack*—for electrochemical reasons discussed elsewhere[8]—thus increasing the intensity of corrosion; larger amounts, however, may stop corrosion altogether. In the absence of stress, waters containing an insufficient amount of an alkaline inhibitor produce pitting and rapid penetration into the steel, so that the treated water will perforate a plate more rapidly than the same water free from inhibitor, although the total destruction of metal is less. Under conditions of corrosion-fatigue, where the attack takes the form of a narrow fissure rather than a hemispherical pit, it might well be expected that small amounts of alkali would increase the rate of penetration of the crack, whereas larger amounts would decrease it, especially since, as shown by Simnad,[7] a lone crack produces far more weakening than a family of cracks close together. The curve corresponding to a peened surface (Fig. 5) shows the decrease of endurance produced by small additions, and suggests, less decisively, that there is a perceptible recovery at high concentrations.

Finely ground (unpeened) specimens show a distinct increase of endurance when alkali is added, although reproducibility here is poor. The behaviour of the specimens is probably connected with the fact that grinding leaves a very complicated system of internal stresses, which are in places favourable to penetration and in other places unfavourable. In a water containing an inhibitor, corrosion-fatigue consists of two stages; a period which elapses before the breakdown of the surface film, and a period needed for the advance of the crack into the interior. In acid, and even in neutral solutions, the first period is short, but the authors have shown[9] that in neutral solutions it is greatly lengthened by the presence of a chromate inhibitor; probably an alkaline inhibitor (sodium carbonate) added to sodium chloride would also lengthen the first period. A rapid penetration of a crack into the interior will require that the position of the breakdown of the film shall coincide with a place where the internal stress conditions in the steel are favourable to rapid extension inwards as a corrosion crack. The probability of a rapid extension inwards will thus be diminished if the number of points of breakdown of the surface skin is diminished, and the addition of inhibitor will accomplish this, thus increasing the life. On the other hand, where the metal just below the surface is in a very uniform condition, breakdown at one point is as likely to produce rapid penetration as breakdown at any other point. If by the addition of inhibitor the attack is concentrated on a limited number of points instead of being distributed over many, the rate of penetration will be increased, not diminished. This may explain why the lives of peened specimens fall below those of unpeened specimens when the concentration of alkaline buffer is sufficient.

Acknowledgments

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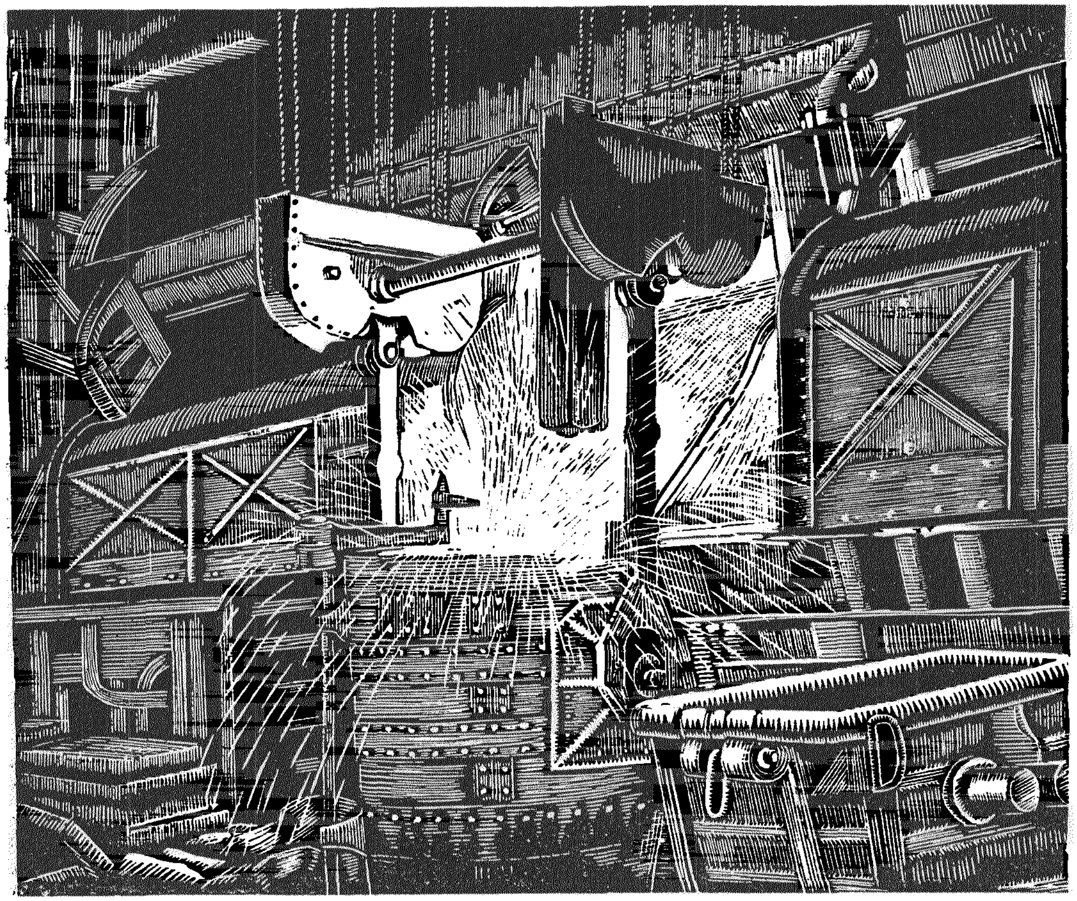

Pouring Liquid Steel—from original woodcut by Viva Talbot