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Effect of Shot-Peening on Fatigue Strength

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Shot-Peening introduces three effects; i.e., (*a*) cold-working, (*b*) residual stress, and (*c*) concentrations. The relation of these effects to fatigue strength is discussed on the basis of data available in the literature. It is shown that the influence of the induced residual stress on the fatigue strength can be predicted on the basis of a concept due to Rosenthal and Sines. Prediction of the strength of manufactured parts and laboratory specimens, based on this concept, agree closely with observed values.

The study reported in this paper was prompted by the need to understand the conditions under which shot-peening is expected to give improved fatigue strength to manufactured parts. During the past 20 years a large amount of experimental data has been published indicating the beneficial effects of shot-peening on the fatigue strength of both laboratory specimens and manufactured parts. It is easier to isolate the effects produced by shot-peening laboratory specimens than it is to isolate the effects produced by shot-peening manufactured parts. Therefore, in this paper, the data from fatigue tests on shot-peened laboratory specimens are studied to isolate the important effects of the shot-peening. Data from fatigue tests on shot-peened manufactured parts are then studied to determine which factors must be considered that were not present in laboratory specimens. Finally, a design procedure is presented for evaluating the influence of shot-peening on fatigue strength.

FATIGUE TESTS OF SHOT-PEENED LABORATORY SPECIMENS

An examination of fatigue data for laboratory specimens enables one to isolate some of the effects produced by shot-peening. The term "laboratory specimen" as used here applies to standard specimens used, for example, in a Krouse or R. R. Moore fatigue machine. A tabulation of the pertinent data is given in Table 1.

Table 1. Fatigue Limits of Several Steels with Various Surface Treatments

Material	Surface Treatment	Fatigue Limit (psi)	% Change
Carburized Nickel-Chromium-Moly. Steel (4)	As received, carburized, then heat treated	58,000	-16
	Surface honed	60,000	-13
	Polished 00 Emery	69,000	0
	Shot-peened	71,000	+ 3
	Shot-peened and honed	74,000	+ 7
Hot-rolled SAE 1020 steel (4)	As received, hot-rolled	28,000	-20
	Polished 00 Emery	35,000	0
	Shot-peened and honed	37,000	+ 6
Tempered spring Steel (5)	As heat treated	87,300	-21
	0.0025" polished from surface, 7μin. finish	110,000	0
	Shot-peened	114,000	+ 4
Chrome-Molybdenum-Nickel Steel (7)	Ground and polished 00 Emery	79,600	0
	Lapped	80,400	+ 1
	Roughened with 24 emery	66,800	-16
	Polished and shot-blasted	81,100	+ 2
	Roughened with 24 emery and shot-blasted	79,600	0
SAE-AISI 4340 Quenched and Tempered to 30 Rockwell C (1)	Polished	65,000	0
	Polished and shot-peened	74,000	+14
	Superfinished	83,000	+28
	Superfinished and shot-peened	73,000	+12

A comparison of the fatigue limits for "as-received" surfaces and polished surfaces shows that polishing increased the fatigue limit about 20 per cent. Roughening an originally polished surface decreases the fatigue limit by about 16 per cent. Shot-peening a polished surface, generally gave an insignificant increase in fatigue strength. In fact, shot-peening a superfinished surface actually reduced the fatigue limit. On the other hand, shot-peening a roughened or "as-received" surface increased the fatigue limit to about the value obtained for a polished surface.

In the light of these observations it appears that a certain fatigue strength is characteristic of the shot-peened surface, regardless of prior surface conditions. In the case of an originally superfinished surface, shot-peening introduced stress raisers that reduced the fatigue limit more than it was increased by beneficial effects such as compressive residual stress. Let us now examine data from fatigue tests on shot-peened manufactured parts to determine if these conclusions are also valid for those cases.

FATIGUE TESTS OF SHOT-PEENED MANUFACTURED PARTS

Considerable literature has accumulated on the beneficial effect of shot-peening manufactured parts. A few representative sets of data will be

TABLE 2 EFFECT OF SHOT-PEENING MANUFACTURED PARTS

Part	Surface finish	Nominal fatigue limit, psi	Per cent increase due to shot-peening
Steering knuckles(1)*	Standard	33000	-
Steering knuckles(1)	Shot-peened	42200	+28
Rear axles (1)	As-forged	26000	-
Rear axles (1)	Shot-peened	38000	+46

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* Numbers in parentheses indicate References at end of paper.

presented to give an estimate of the improvement in fatigue strength to be expected by shot-peening.

Table 2 shows the improvement in fatigue limit obtained by shot-peening two manufactured parts. The fatigue limit of the as-forged axles was only 26 per cent of the fatigue limit as determined by laboratory tests in R. R. Moore rotating bending fatigue machines. The principal factors contributing to the decreased fatigue strength for the as-forged parts were said to be surface decarburization and surface roughness.

Mattson (2) found the fatigue life of shot-peened leaf springs increased by a factor of 10. Sachs (3) discussed a case in which shot-peening raised the fatigue strength of a decarburized surface of SAE 4340 steel to that of a carefully machined surface.

It is thus well-established that, at least in many instances, shot-peening improves the fatigue strength of service parts. The shot-peening has at least partially removed the effects of poor surface finish and residual tensile stresses on the surface of the part, or it has set up beneficial effects which counterbalance these deleterious effects. It is the uncertainty in the condition of the surface and the residual stresses in service parts before shot-peening which account for the improved fatigue strength. On the other hand, simple laboratory specimens, such as are used in R. R. Moore fatigue machine, are prepared carefully and the surface conditions are known. The effects introduced by shot-peening are easier to evaluate in this case.

Comparison of Fatigue Data for Shot-Peened Manufactured Parts and Simple Laboratory Specimens

The increase in the fatigue limit of polished laboratory specimens due to shot-peening varies from 2 to 14 per cent, Table 1. In contrast, the improvement in the fatigue strength of manufactured parts is variously reported from 18 to 46 per cent (1, 2, 3). However, if the improvement in the fatigue strength due to shot-peening the "as-received" or "roughened" surface for both laboratory specimens and manufactured parts is computed a somewhat more consistent result is obtained.

Shot-peening increased the fatigue strength of the "as-received" or "roughened" surface by 19 to 32 per cent, and polishing increased the fatigue strength 19 to 26 per cent. The conclusion is that either polishing or shot-peening a roughened or as-received surface gives a substantial improvement in fatigue strength; the shot-peening is only slightly more beneficial than polishing.

FACTORS INTRODUCED BY SHOT-PEENING

For some time it has been recognized that at least three effects are introduced by shot-peening (4, 8):

1 Cold working.
2 Residual stress.
3 Stress concentrations.

The relative effects of these three factors have not been established. However, the results of a sufficient number of investigations have been reported to indicate, in a qualitative manner, the significance to be attached to each of these factors. In this section each of these factors is discussed.

Cold-Working

The beneficial effect of cold-working on fatigue strength has been established by several investigators. Moore and Kommers (9) reported an increase in the fatigue strength of 0.18 per cent carbon-steel bars that had been pulled well into the plastic region, stress-relieved, and fatigue tested. For bars stretched between the yield point and the ultimate strength, the fatigue limit was increased 25 per cent. Bars stretched to the ultimate strength has a 46 per cent increase in fatigue limit.

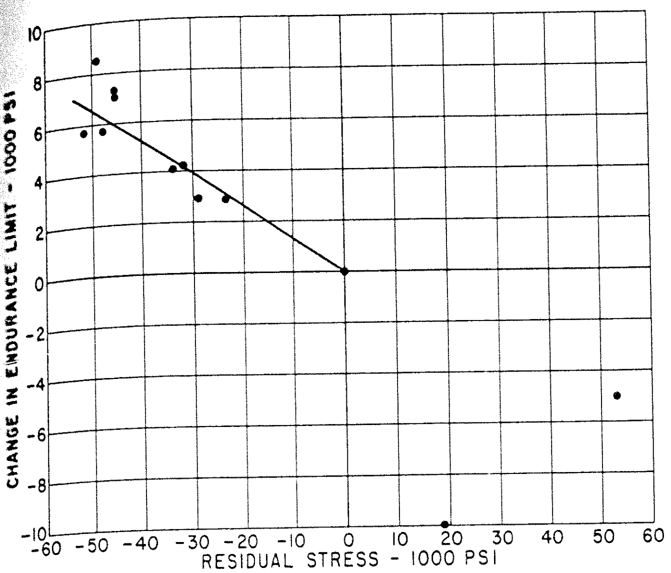

Fig.1 Effect of residual stress on fatigue limit (reference 15, 16).

Later tests of the same kind on a higher carbon steel by Horger and Maulbetsch (10) gave similar results. Horger and Maulbetsch (10) also gave the results of fatigue tests on specimens removed from successive layers of a 0.45 per cent carbon-steel shaft, 2 in. diam. Vickers diamond pyramid hardness measurements indicated the cold-working had increased the hardness to a depth of 1/4 in. The specimens had a progressive increase in fatigue strength from 37,500 to 43,000 psi as they were taken from layers nearer the surface.

In all these experiments on the effects of cold-working, the residual stresses were not measured. One naturally assumes that concentric tensile loading produces uniform stress, and consequently residual stress does not occur. It has been observed, however, that the surface flows more easily than the interior, causing a definitely measurable hardness gradient across the diameter, and it can be shown that there should be a residual-stress pattern associated with such a hardness pattern that is characterized by favorable surface compression. Considering the uncertainty as to whether strengthening is due to cold work or residual stress, let us turn attention now to investigations where both cold work and residual stress were known to have been present.

Peterson and Lessells (11) refer to the work of Thum and Bautz (12), who used the boring-out technique to find the residual stress; they concluded that 80 per cent of the increase in fatigue strength was due to residual stress, the remaining 20 per cent being attributed to cold-working or a physical change in the surface of the material. For some cases, Peterson, and Lessells (11) were inclined to attribute a greater percentage of the increase in fatigue strength to changes in the physical properties of the metal produced by cold-working. Nevertheless, they emphasized that it was not implied that residual stresses had no effect or that they cannot be important in some cases. In a series of papers Mattson (13, 14) discusses the beneficial effects of residual surface compressive stresses produced by shot-peening. These stresses were about 60 per cent of the yield strength for hard materials and somewhat higher for softer materials due to the increase in the yield strength resulting from the peening. However, Mattson does not rule out the beneficial effect of cold-working which he states may be significant, but it cannot be measured as residual stresses can be.

In short, the relative beneficial effects of cold-working and residual stress on fatigue strength have not been established.

Residual Stress

Recently, with improved measurement techniques, greater emphasis has been given to the effect of residual stress on fatigue strength. Probably the earliest, and still the most comprehensive, investigation on this subject was performed by Buhler and Buchholtz (15, 16). The residual stresses were introduced into carbon steels by quenching from the tempering temperature. They were measured by mechanical dissection and were found to vary from 40 to 100 per cent of the yield strength. Residual surface compressive stresses increased the fatigue limit an average of 13 per cent, the range of increase being 6 to 22 per cent. The greatest increase occurred for the specimen having the largest residual compressive stresses. Residual surface tensile stresses decreased the fatigue limit 12 to 16 per cent, with an average decrease of 14 per cent. The change in the fatigue limit with residual stress is shown in Fig. 1.

Stress Concentration

The detrimental effect of stress raisers on fatigue strength is well known, but there is no direct measurement of how large this effect is for the roughness of a shot-peened surface. The data of Horger and Neifert (8), as shown in Table 3, furnish indirect evidence as to how large the surface-roughness effect might be.

The three surface smoothness conditions given in Table 3 are described as follows:

1 Photomicrographs showed notches and sharp surface discontinuities.

2 Relatively smooth surface, consisting of shallow, circular indentations.

TABLE 3 EFFECT OF SHOT SIZE USED IN PEENING ON FATIGUE LIMIT

Surface condition	Arc height in 0.001 in. (a measure of residual stress) Almen-Strips		Fatigue limit, psi	Per cent change	Surface smoothness
	A	C			
Polished--not shot-peened	0	0	31000	0	Excellent
No. 28 shot (0.0188 in.) 1	9-11.5	3-3.5	32000	3	Poor 1
No. 22 shot (0.0315 in.) 2	17.5	6.5	37000	19	Good 2
No. 19 (0.055 in.) 3	19.0	9-11	34000	10	Fair 3

3 Intermediate surface roughness between "good" and "poor."

The table shows that the fatigue strength for No. 22 shot, where the surface is good, is 8 per cent higher than the fatigue strength for No. 19 shot, where the surface is only fair, even though the favorable residual stress is higher for the No. 19 shot. This means that there would be more than 8 per cent difference in the K_f-values for two conditions of shot-peening if there were the same residual stress for both conditions. The results using No. 28 shot show that the detrimental effects of a poor surface can counteract almost wholly the beneficial effects of residual stress.

Polishing after shot-peening also serves to show the effect of the surface roughness caused by the peening. Coombs and his co-workers (5) found that the fatigue strength for a given (good) polish is 22 per cent higher when the polishing has been preceded by shot-peening, because of surface compression and possible cold work. With shot-peening and no subsequent polishing the net gain in fatigue strength over a polished surface was insignificant. It may be concluded that the surface roughness due to shot-peening is a potent factor, whose detrimental effects may almost completely counteract the beneficial effects due to residual stress and cold work.

RATIONAL ANALYSIS OF EFFECT OF SHOT-PEENING

In the previous sections, a summary has been presented regarding the effects of the three principal factors introduced by shot-peening; namely, cold-working, residual stress, and stress concentrations. Although the relative benefit of cold-working and residual stress are still controversial, it will be shown in this section that a rational procedure now exists for predicting the increase in fatigue strength due to shot-peening. This method neglects the effect of cold-working and takes account only of residual stress and stress concentrations.

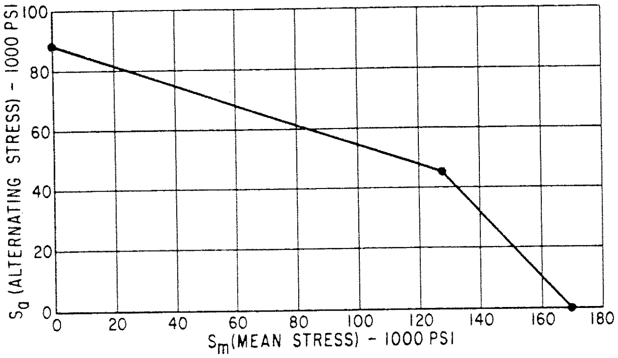

Fig.2 Haigh-Soderberg diagram for unstraightened crankshafts (reference 19).

The premise on which this method is based is that residual stress may be treated as a mean stress in a Haigh-Soderberg, or similar, diagram. The earliest reference which has been found to this method of treating residual stress is given in (18). A typical Haigh-Soderberg diagram is shown in Fig. 2. In this diagram, the mean stress is the abscissa and the alternating stress is the ordinate for a prescribed fatigue life, 10^7 cycles in this case.

One of the first attempts to treat the residual stress as a mean stress is discussed by Horger and Neifert (19) using data obtained by Schmidt (20). Schmidt determined the fatigue strengths of unstraightened crankshafts and crankshafts straightened by plastic bending. The Haigh-Soderberg diagram obtained from tests on the unstraightened crankshafts is shown in Fig. 2. As indicated in this figure, the reversed bending fatigue strength was 87,000 psi.

The residual longitudinal tensile stresses produced in the crankshaft fillet by straightening

TABLE 4 STANDARD PROPERTIES OF ALUMINUM

Alloys Used by Rosenthal and Sines (21)	61S-T	61S-0
0.2 per cent yield strength, S_y, psi	40000	16000
Ultimate strength, psi	45000	25700
Smooth bar fatigue strength, S_e, psi	14500 5×10^8 cycles	11500 1×10^7 cycles
S_e/S_y	0.338	0.718

were measured by the X-ray diffraction technique before fatigue testing and were found to be between 85,000 and 100,000 psi. Referring to Fig. 2, and using the residual stress of 100,000 psi as a mean stress, the fatigue strength is found to be 54,000 psi. The measured fatigue strength was found by experiment to be 70,000 psi.

In analyzing this discrepancy between the predicted and measured fatigue strengths, it was realized that perhaps the residual stresses were decreased during cyclic loading (fading). In order to pursue this possibility, the residual stress in a plastically straightened crankshaft after it was subjected to 5×10^5 cycles of alternating stress was measured by X-ray diffraction and it was found to have been reduced to 48,000 psi. Using this stress as a mean stress in the Haigh-Soderberg diagram, the alternating stress is 71,000 psi. This value compared quite well with the experimentally determined value of 70,000 psi.

This investigation indicates that the fatigue strength can be predicted neglecting the effect of cold-working if the residual stress is treated as a mean stress and if the fading of residual stress is taken into account.

In applying these concepts to the prediction of fatigue strength of shot-peened specimens two additional items of information are needed:

1 How can the fading of residual stress be predicted?

2 What is the method of treating stress concentrations? Several investigators, notably Rosenthal and his co-workers, have provided both the principles and supporting experimental data for answering these questions.

Considering first the problem of fading of residual stresses, Norton and Rosenthal (18) state that residual stresses decrease during cyclic loading when the unnotched bar fatigue limit is 60 per cent or more of the yield strength. Therefore, the criterion for fading is the ratio of the fatigue limit of unnotched polished specimens to the yield strength. This is merely the criterion, the actual method of treating fading will be considered along with a study of the second question regarding stress concentrations, since in the investigations discussed here these two effects were considered together.

Rosenthal and Sines (21) investigated the fading of residual stresses in 61S-T and 61S-0 notched bars during fatigue testing, and the effect of those residual stresses on fatigue strength. The properties of the materials are given in Table 4.

The specimens were first plastically prestrained in tension or compression to produce residual stress at the root of the notch and then they were tested in reversed bending or with equal mean and alternating stress components. Residual stress was measured locally with X-rays.

Measurements of nominal fatigue strength and local residual stress before and after cycling are shown in Table 5.

The tabulated values of initial residual stress are averages of several measurements.[2] Values of these same quantities, calculated according to the concept of Rosenthal and Sines are also shown for comparison. The concepts of Rosenthal and Sines are as follows:

1 The residual stresses will not be changed by cycling if maximum total stress is less than the yield strength. The maximum total stress is the maximum sum of residual stress, mean load stress and alternating load stress.

2 Residual stress may be treated as a mean stress. The equilibrium value (after cycling) should be used.

3 The curve of nominal mean stress versus nominal alternating stress for notched bars can be obtained from the unnotched curve by dividing both abscissas and ordinates by K_f.

4 Cold-work effects can be disregarded.

These concepts are based on unconventional assumptions concerning the fatigue behavior of the material in a region of stress concentration. Therefore, it is worth while to tabulate these assumptions:

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[2] In some cases the values were obtained by calculation using the method of (22).

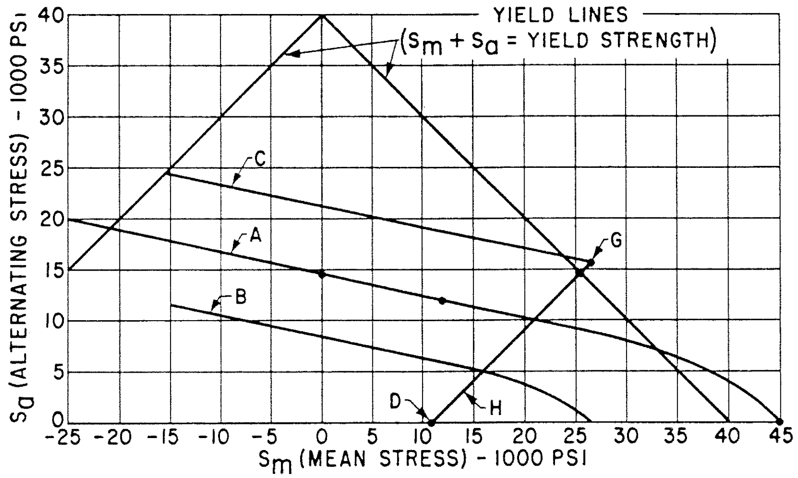

Fig.3 Haigh-Soderberg diagram for 61S-T (reference 21).

1 The maximum nominal stress at the fatigue limit for a notched specimen is equal to the maximum stress at the fatigue limit for unnotched specimens divided by the strength reduction factor, K_f. This means that in a Haigh-Soderberg diagram for unnotched fatigue strength both the mean and alternating components of stress are to be divided by K_f. The strength-reduction factor represents the response of the material to the effect of biaxial stress, steep stress gradient, strain-hardening, and possibly other effects.

2 The true maximum local stress at the root of the notch is equal to the maximum nominal stress multiplied by K_t. In a Haigh-Soderberg diagram for the nominal fatigue strength for notched specimens, both the mean and alternating components of stress and multiplied by K_t to get local stress.

3 The actual maximum local stress cannot greatly exceed the yield strength. If the maximum local stress at the beginning of cyclic loading does exceed the yield strength, the stress will be decreased by plastic flow until the actual maximum local stress is equal to the yield strength (or slightly greater, because of strain hardening).

4 The local residual stress is treated in the same manner as the local mean load stress. The maximum stress is the sum of local mean and alternating load stresses and local residual stress.

5 If the sum of local load stress and residual stress does exceed the yield strength, the residual stress will change until the maximum stress is approximately equal to the yield strength.

The use of these assumptions in predicting the fatigue strength for 61S-T and 61S-O is shown graphically in Figs. 3 and 4. A description of the construction of these figures follows.

In Figs. 3 and 4 the Haigh-Soderberg diagram is drawn for unnotched specimens. These curves, marked A, are drawn through experimental values of alternating stress mean stress ratios (S_a/S_m) of 0, 1, and ∞.

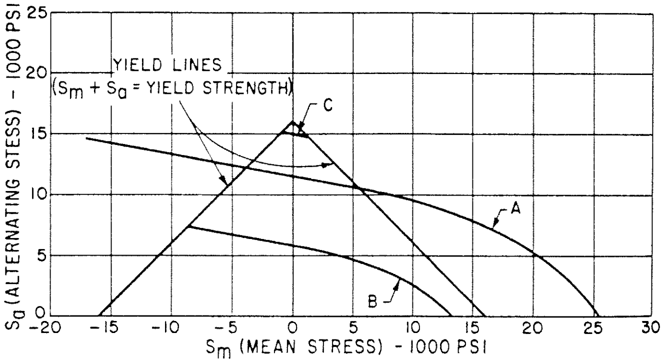

Fig.4 Haigh-Soderberg diagram for 61S-O (reference 21).

Curve B in Figs. 3 and 4 describe the nominal fatigue strength for notched specimens. These curves were obtained by dividing both alternating and mean components of stress by K_f, as postulated by Rosenthal and Sines. The strength-reduction factor, K_f, was determined for reversed bending ($S_m = 0$ or $S_a/S_m = \infty$) to be 1.70 for 61S-T and 1.92 for 61S-O.

Curves C in Figs. 3 and 4 were obtained by multiplying the abscissas and ordinates of Curves B by the theoretical stress concentration factor, $K_t = 2.5$. These curves represent the local stress at the root of the notch if the local peak stress does not cause plastic flow, that is, for the part of the curve lying well inside the yield lines. The actual local stress at the yield lines is probably somewhat smaller than that indicated by Curves C, because the small amount of plastic de-

Table 5

Predicted and Measured Fatigue Limits for 61S-T and 61S-0 with Residual Stress Present

Test No.	Material	Type of Test	Initial Residual stress psi	Residual stress after 10^7 cycles psi	Predicted residual stress at equilibrium psi	Measured Fatigue Limit psi	Fatigue Limit Using C Value psi	% Error
1	61S-T	reversed bending	-16,500	-13,000	-15,500	11,000	9,600	-14
2	61S-T	reversed bending	plus (not measured)	+24,000	+24,000	6,000	6,500	+ 8
3	61S-T	mean stress = alt. stress	-16,500	-11,000	---**	8,800	7,800	-11
4	61S-T	mean stress = alt. stress	plus (not measured)	+11,000	+ 8,000	5,800	6,300*	+ 8
5	61S-0	reversed bending	0	0	0	6,000	6,000	0
6	61S-0	reversed bending	negative (not measured)	- 1,300	- 1,000	6,000	6,100	+ 1
7	61S-0	mean stress = alt. stress	0	- 9,300	-13,200	5,500	5,640*	+ 3
8	61S-0	mean stress = alt. stress	negative (not measured)	-10,600	-13,200	5,500	5,750*	+ 4

* Values somewhat too high because of errors in curve C arising from plastic flow.

** Not calculable quantitatively. Will be moderately less than 16,500 compression.

formation at the yield strength generally results in local stresses that are somewhat less than K_t times the nominal stress. However, Curves C probably represent a good approximation to the local stress where they intersect the yield lines. The approximation that local stress equals K_t times nominal stress is less and less accurate for points farther and farther out on Curves C beyond the yield lines. The true local stress in the region outside the yield lines is probably represented by a curve lying somewhere between Curve C and the yield line. Consequently, the local stress values read off from Curves C outside the yield lines must be considered as fictitiously high.

Curve C has been used to predict the nominal notched fatigue strengths of specimens with and without residual stress. These predictions are shown in Table 5. The prediction is made as follows: The ordinate of Curve C is read off at the point where the abscissa is the sum of the local values, the equilibrium residual stress and the mean load stress, and this value of local alternating stress is divided by K_t to get nominal alternating stress.

For example, Table 5 shows that one of the 61S-T specimens tested under conditions of equal mean and alternating stress has an equilibrium residual tensile stress of 11,000 psi. This stress is laid off on the abscissa, locating point D in Fig. 3. The 45-deg line H. represents the superimposed testing condition of equal mean and alternating components of the load stress. The intersection of this line with Curve C represents failure. Considering Rosenthal and Sines criterion (Curve C), the failure point is at G representing a local alternating stress of 15,700 psi (the ordinate). The nominal alternating stress is found by dividing by $K_t = 2.5$. This results in a value of 6300 psi, recorded in the seventh column of Table 5, which agrees with the measured value of 5800 psi within 8 per cent.

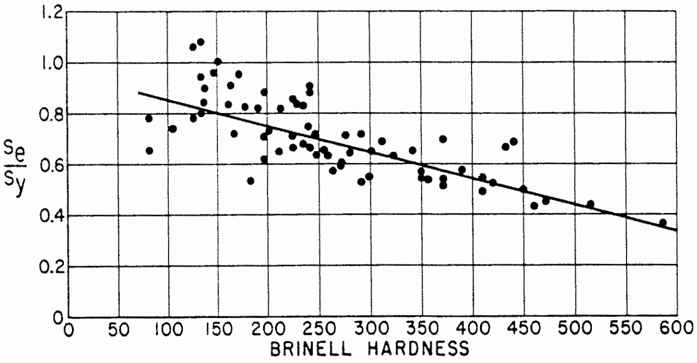

Fig.5 Ratio of fatigue limit to yield strength versus Brinell hardness, steel and steel alloys (reference 24).

Similar comparisons in Table 5 for all the tests show that the predicted values are within ± 14 per cent. The conclusion to be drawn from this good correlation between measured and predicted fatigue strengths is that the local equilibrium residual stress can be treated as part of the mean stress in a Haigh-Soderberg diagram pertaining to local stress components.

On the basis of Rosenthal and Sines' concept, Figs. 3 and 4 serve also to predict the equilibrium values of residual stress (that is, after cycling).

According to this concept, the initial residual stress will not change if the failure point on Curve C that corresponds to the initial residual stress lies between the yield lines. By extending this concept slightly, it can be shown that an initial residual stress which corresponds to a failure point outside the yield lines will change (fade) until the failure point moves to the nearest yield line.

All the data conform roughly to the concept that the initial residual stress values will not change if the corresponding failure points are inside the yield lines. If the failure point corresponding to the initial residual stress is outside the yield lines, the residual stress will change with cycling until the failure point moves to the nearest yield line. The only exception is a minor fading on the failure side (tension) resulting from plastic flow and considerable fading on the compression side.

CONCLUSIONS

The conclusions regarding the effectiveness of residual stress, according to Rosenthal and Sines' data, can now be enumerated.

1 The steeper the Haigh-Soderberg diagram, the more effective is the residual stress.

2 Residual stress becomes less effective as the ratio of K_t to K_f increases, because the intercept between the yield lines becomes shorter.

3 Residual stress becomes less effective as the fatigue limit becomes a larger and larger fraction of the yield strength.

4 Percentage-wise, the effectiveness of residual stress will be smaller, if anything, for notched specimens than for unnotched ones.

These conclusions apply only to situations where polished specimens have been subjected to a surface treatment involving residual stress. As discussed earlier, there may be considerably larger improvements by shot-peening a roughened or as-heat-treated surface. The mechanism of this improvement is not yet clear.

Other investigators have also stated that the relative beneficial effect of residual stresses is dependent on the ration, S_e/S_y. The build-up of residual stresses is initially stress-free specimens has also been reported by various investigators (15). Harris (23) states that shot-peening is beneficial in steels having endurance ratios below 0.45 to 0.50. Mattson (14) states that the maximum residual stress due to shot-peening is about 60 per cent of the yield strength and is somewhat higher for softer materials. He also indicates that the selection of shot-peening and surface rolling treatments should be based on hardness. In this connection it is interesting to note that there is a general trend of decreasing value of S_e/S_y with increasing hardness as shown in Fig. 5. For a material having a high hardness, the unnotched bar fatigue limit is considerably less than the yield strength. Therefore, residual stresses would be expected to have a significant effect on the fatigue strength.

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