During the last twenty years numerous papers have been published in which the beneficial effects of shot-peening are discussed. The results of fatigue tests are presented for two types of specimens: service parts such as springs, axles and crankshafts and laboratory specimens such as are used in a R. R. Moore or Krouse fatigue testing machine. The beneficial effects of shot-peening service parts are usually more pronounced than the beneficial results of shot-peening laboratory specimens. On the other hand, it is more difficult to isolate the effects of shot-peening producing an increased fatigue strength of service parts than it is to isolate these effects in shot-peened laboratory specimens. In this paper some of the results which are available in the literature for fatigue tests on service parts will be presented, followed by the results of fatigue tests on laboratory specimens. The factors responsible for the increased fatigue strength will then be isolated and treated in a rational manner where possible.

I. Fatigue Tests of Shot-Peened Service Parts

Considerable literature has been accumulated in the past on the beneficial effect of shot-peening service parts. A small number of representative references will be reviewed to give support to this statement.

Garwood, Zurburg and Erickson (1)* made reversed bending fatigue tests on taxicab steering knuckles made of SAE 4052 steel. These parts had fillets, resulting in a theoretical stress concen-

* Numbers in parenthesis indicate references

tration factor of 1.80, determined photoelastically. The strength reduction factor was 1.67, giving a notch sensitivity factor of 0.84. The results obtained from the fatigue tests are shown in Table I.

TABLE I

Effect of Shot-peening Steering Knuckles

Part	Nominal Fatigue Limit (psi)	% Increase
Standard	33,000	0
Shot-peened	42,200	28

The same group of investigators (1) also reported on reversed bending tests of automotive rear axles made of SAE-AISI 4063 steel, as given in Table II.

TABLE II

Effect of Shot-peening Rear Axles

Surface Condition	Fatigue Limit (psi)	% Increase
As forged	26,000	0
Shot-peened	38,000	31

The fatigue limit of the as-forged axles was only 26% 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 <u>life</u> of shot-peened leaf springs increased by a factor of ten. 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 make it difficult to assess the factors introduced by 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 carefully prepared and the surface conditions are known. The effects introduced by shot-peening are easier to evaluate in this case.

II. Fatigue Tests of Shot-Peened Laboratory Specimens

The results of some typical fatigue tests on simple laboratory specimens which have been shot-peened are presented in this section. H. F. Moore (4) found the fatigue limits for various surface conditions for two steels shown in Table III and IV.

TABLE III

Carburized Nickel - Chromium - Molybdenum Steel, with Various Surface Treatments

	Surface Treatment	Fatigue Limit (psi)	% Change
(1)	As received, carburized, then heat treated	58,000	-16
(2)	Surface honed	60,000	-13
(3)	Polished 00 emery cloth	69,000	0
(4)	Shot-peened	71,000	+ 3
(5)	Shot-peened and honed	74,000	+ 7

TABLE IV

Hot-rolled SAE 1020 Steel with Various Surface Treatments

	Surface Treatment	Fatigue Limit (psi)	% Change
(1)	As received, hot-rolled	28,000	-20
(2)	Polished 00 emery cloth	35,000	0
(3)	Shot-peened and honed	37,000	+ 6

A substantial increase in the fatigue strength was obtained by polishing the surface of the specimens. However, shot-peening the polished surface gave only a small increase in fatigue strength. The fatigue strength was increased slightly more by honing the shot-peened surface.

Recently fatigue data (5) have been published on rotating bending tests on specimens of hardened and tempered spring steel which were shot-peened. These results are given in Table V.

TABLE V

Shot-peened Tempered Spring Steel

	Surface Condition	Fatigue Limit (psi)	% Change
(1)	As heat treated	87,300	-21
(2)	0.0025" polished from surface, 7micro-inch finish	110,000	0
(3)	Shot-peened	114,000	+ 4

The shot-peened specimens were only slightly stronger than the polished specimens.

Hanley and Dolan (6) published the results of rotating bending fatigue tests performed by Wiegand (7). These data are given in Table VI.

TABLE VI

Effect of Surface Finish on Fatigue Limit

	Surface Finish	Fatigue Limit (psi)	% Change
(1)	Ground and polished 00	79,650	0
(2)	Lapped	80,350	+ 1
(3)	Roughened with 24 emery cloth	66,850	-16
(4)	Polished and shot-blasted	81,100	+ 2
(5)	Roughened as in (3) and shot-blasted	79,650	0

The shot-blasting gave no significant improvement in the fatigue strength of polished specimens. Roughening of the surface reduced the fatigue strength by 16% and shot-blasting the roughened surface restored the fatigue strength to that for polished specimens.

In other words, if one starts with a roughened or "as-heat-treated" surface, a considerable improvement in strength can be made by shot-peening, but not much more than by polishing. Furthermore, approximately the same final strength can be obtained by shot-peening a roughened or as received surface as by shot-peening a polished surface.

The fact that a certain fatigue strength is a characteristic of the shot-peened surface, regardless of prior surface conditions, can also be seen from the data (1) of Table VII.

TABLE VII

Effect of Shot-peening and Superfinishing

Surface Condition	Fatigue Limit (psi)	% Change
Polished	65,000	0
Polished and shot-peened	74,000	+14
Superfinished	83,000	+28
Superfinished and shot-peened	73,000	+12

In this case the shot-peening has raised the strength of the polished specimens presumably because the beneficial effects of residual stress predominate; but the shot-peening has lowered the strength of the superfinished specimens, presumably because the detrimental effects of surface roughness predominate. Thus, the question here is not "Why does shot-peening strengthen in one case and weaken in another?", but rather "Why are the strengths so different for two different degrees of polishing?".

III. Comparison of Fatigue Data for Shot-peened Service Parts and Simple Laboratory Specimens

The increase in the fatigue strength of service parts due to shot-peening is variously reported from 18 to 43% according to references cited in Section I. In contrast, the improvement in fatigue strength of polished laboratory specimens discussed in Section II varies from 2 to 14%. However, if the improvement in fatigue strength due to shot-peening the "as received" or "roughened" surface is computed, the results shown in Table VIII are obtained

TABLE VIII

Effect of Shot-peening and Polishing

Data from Table	Fatigue Limit (psi)	% Increase	
		Polished	Shot-Peened
I	As received - 58,000	19	22
II	As received - 28,000	25	32
III	Roughened - 66,850	19	19
IV	As received - 87,300	26	30

Shot-peening increased the fatigue strength of the "as received" or roughened surface by 19 to 32%, and polishing increased the fatigue strength 19 to 26%.

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.

In the light of the results shown in Tables III to VIII, the seeming discrepancy between the effects of shot-peening manufactured parts and laboratory specimens no longer causes any confusion. It has been customary to express the effect of shot-peening as the improvement over polishing for laboratory specimens, but as the improvement over as-received surfaces for manufactured parts.

For proper comparison of the effects of shot-peening on manufactured parts and laboratory specimens, the improvement over as-received surfaces should be stated in both cases. When this is done, it is found that shot-peening manufactured parts gives 18 to 43% improvement, Tables I and II and References (2) and (3), while shot-peening laboratory specimens gives 19 to 32% improvement (Table VIII). Thus, the improvements are quite similar for the two cases.

The improvement attained by shot-peening on as-received surface is undoubtedly a complex effect involving residual stress, surface roughness, cold work, and possibly other factors. In the next section an attempt will be made to isolate the effects of these factors for the simpler situation where the surface is polished before the shot-peening.

IV. Factors Introduced by Shot-peening

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

(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.

(1) 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% carbon steel bars which had been pulled well into the plastic region, stress relieved, and fatigue tested. These bars were supposed by the authors to be free of residual stress, but no measurements were made to verify this condition. The results obtained from the fatigue tests are given in Table IX.

TABLE IX

Effect of Prestretching on Fatigue Limit

Cold Working	Fatigue Limit (psi)	% Change
Unstretched	28,000	0
Stretched between Y.P. and ultimate	35,000	25
Stretched to ultimate	41,000	46

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% carbon steel shaft, 2 inches in diameter. Vickers diamond pyramid hardness measurements indicated the cold working had increased the hardness to a depth of ¼ inch. The specimens had a progressive increase in fatigue strength from 37,500 psi to 43,000 psi as they were taken from layers nearer the surface. The authors presumed the residual stresses to be small and they attributed most of the increase in fatigue strength to cold working.

In all the above 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 such as that shown in Table IX 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% of the increase in fatigue strength was due to residual stress, the remaining 20% 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 the 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% 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.

(2) 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% of the yield strength. Residual surface compressive stresses increased the fatigue limit an average of 13%, the range of increase being 6 to 22%. The greatest increase occurred for the specimens having the largest residual compressive stresses. Residual surface tensile stresses decreased the fatigue limit 12 to 16%, with an average decrease of 14%. The change in the fatigue limit with residual stress is shown in Figure 1.

(3) Stress Concentration

The detrimental effect of stress raisers on fatigue strength is well known, but there are no direct measurements 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 X, furnishes indirect evidence as to how large the surface roughness effect might be.

TABLE X

Effect of Shot Size Used in Peening on Fatigue Limit

Surface Condition	Arc height in 0.001 in. (a measure of residual stress) Almen A	Strips C	Fatigue Limit (psi)	%Change	Surface Smoothness
Polished-not shot-peened	0	0	31,000	0	excellent
No. 28 shot (0.0188 in.) 1	9-11.5	3-3.5	32,000	3	poor 1
No. 22 shot (0.0315 in.) 2	17.5	6.5	37,000	19	good 2
No. 19 (0.055 in.) 3	19.0	9-11	34,000	10	fair 3

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

1. Photomicrographs showed notches and sharp surface discontinuities.
2. Relatively smooth surface, consisting of shallow, circular indentations
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% 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% 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 almost wholly counteract the beneficial effects of residual stress.

Polishing after shot-peening (5) also serves to show the effect of the surface roughness caused by the peening. Table XI shows that the fatigue strength for a given (good) polish is 22% higher when the polishing has been preceded by shot-peening, because of surface compression and possible cold work.

TABLE XI

Effect of Removing Surface Layers

from Shot-peened Specimens

Surface Condition	Fatigue Limit (psi)	% Change
As heat treated	87,300	-21
0.0025" polished from surface, 7 μ in. finish	110,000	0
Shot-peened	114,000	+ 4
Shot-peened, 0.0039" polished from surface, 7 μ in. finish	134,000	+22

However, most of this benefit was counteracted by the 18% weakening due to the roughness of the peened surface, resulting in a net gain over the polished surface of only 4%. Note also from Table XI that either shot-peening or polishing gives at least 20% strengthening over the as-heat-treated bars.

From Tables X and XI 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.

Several investigators have shown that a higher fatigue limit is obtained for cold-rolled than for shot-peened surfaces. For example, in a Russian publication (17) the values given in Table XII were presented for spring steel.

TABLE XII

Effect of Shot-peening and Cold-rolling Spring Steel

Surface Condition	Fatigue Limit (psi)	% Increase
Polished	69,200	0
Shot-peened	76,000	10
Cold-rolled	88,800	28

Since surface roughness is somewhat less severe for cold-rolled than for shot-peened specimens, it is reasonable to suppose, in the light of the previous conclusion, that the greater improvement by cold-rolling than by shot-peening is due to the fact that there is less detrimental effect of surface roughness to counteract the beneficial effects of residual stress.

V. Rational Analysis of the 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: 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.

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 Figure 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 on Figure 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 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 Figure 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 strength, 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% 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 61ST and 61SO notched bars during fatigue testing, and the effect of those residual stresses on fatigue strength. The properties of the materials are given in Table XIII.

TABLE XIII

Standard Properties of Aluminum

Alloys used by Rosenthal and Sines (21)	61S-T	61S-O
0.2% yield strength, S_y, psi	40,000	16,000
Ultimate strength, psi	45,000	25,700
Smooth bar fatigue strength, S_e, psi	14,500 @ 5×10^8 cycles	11,500 @ 1×10^7 cycles
S_e/S_y	0.338	0.718

The specimens were first plastically pre-strained 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 XIV.

TABLE XIV

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

Test No.	Material	Type of Test	Initial Residual stress	Residual stress after 10^7 cycles	Predicted residual stress at equilibrium	Measured Fatigue Limit	Fatigue Limit Using C Value	Fatigue Limit Using C %Error	Fatigue Limit Using C' Value	Fatigue Limit Using C' %Error
1	61ST	reversed bending	-16,500	-13,000	-15,500	11,000	9,600	-14	9,200	-20
2	61ST	reversed bending	plus (not measured)	+24,000	+24,000	6,000	6,500	+ 8	7,300*	+22
3	61ST	mean stress =alt. stress	-16,500	-11,000	---**	8,800	7,800	-11	8,100	- 8
4	61ST	mean stress =alt. stress	plus (not measured)	+11,000	+ 8,000	5,800	6,300*	+ 8	7,100*	+22
5	61SO	reversed bending	0	0	0	6,000	6,000	0	6,000	0
6	61SO	reversed bending	negative (not measured)	- 1,300	- 1,000	6,000	6,100	+ 1	6,100	+ 1
7	61SO	mean stress =alt. stress	0	- 9,300	-13,200	5,500	5,640*	+ 3	5,800*	+ 5
8	61SO	mean stress =alt. stress	negative (not measured)	-10,600	-13,200	5,500	5,750*	+ 4	5,840*	+ 6

* Values somewhat too high because of errors in curves C and C' arising from plastic flow.

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

The tabulated values of initial residual stress are averages of several measurements.*

Values of these same quantities, calculated according to the concepts of Rosenthal and Sines and other common concepts, 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 vs 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 worthwhile to tabulate these assumptions and discuss their significance:

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

* In some cases the values were obtained by calculation using the method of Ref. 22.

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_f. In a Haigh-Soderberg diagram for the nominal fatigue strength for notched specimens, both the mean and alternating components of stress are 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 61ST and 61S-0 is shown graphically in Figs. 3 and 4. A description of the construction of these figures is given below.

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 ∞.

Curves 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 61ST and 1.92 for 61S-0.

Curves B' are shown for comparison purposes and were obtained by dividing only the alternating component of stress by K_f. This is the customary method of determining the nominal notched fatigue strength.

Curves C of 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 deformation 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.

Curves C' represent the local stresses corresponding to nominal stress curves B'. These curves have been drawn so that predictions of notch fatigue strength can be made on the basis of assumed Curves B', in addition to predictions from Rosenthal and

Sines' assumed Curves B. Curves C' are subject to errors outside the yield lines for the same reasons as Curves C.

Curves C and C' have been used to predict the nominal notched fatigue strengths of specimens with and without residual stress. These predictions are shown in Table XIV, page 20. The prediction is made as follows: the ordinate of Curve C or 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 aternating stress is divided by K_t to get nominal alternating stress.

For example, Table XIV shows that one of the 61ST specimens tested under conditions of equal mean and alternating stress had 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 degree 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 or 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 XIV, which agrees with the measured value of 5800 psi within 8 per cent. In a similar manner, but using Curve C' instead of Curve C, a predicted value of 7100 psi is obtained.

Similar comparisons in Table XIV for all the tests show that the predicted values are within ± 10 to 20 per cent depending on the method of calculating the nominal Haigh-Soderburg curve for notched specimens. Rosenthal and Sines concept of applying K_f to both stress components yields the better result. 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 1, p. 21, 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.

Of the four tests where residual stresses were measured both before and after cycling, No. 5 had a failure point, based on initial residual stress, that falls inside the yield lines and

Nos. 1, 3 and 7 had failure points outside the yield lines. These failure points are the intersection of Curves C with the various dashed loading lines shown in Figs. 3 and 4.

For tests 1 and 7, fading occured so as to put the failure point at the intersection of Curve C and the yield lines. For test 3, the loading conditions and initial residual stress were such as to cause yielding on the compression side but not on the tension side. This can be shown to cause the residual stress on the compression side to fade essentially to zero, which has the auxiliary effect of reducing the residual stress somewhat on the tension side. This reduction of stress was actually observed (see Table XIV).

For tests 2, 4, 6, and 8 where the sign of the initial residual stress is known but not the magnitude, the measured final residual stress value is consistent with the residual stress changes that are expected because of the plastic flow. The failure points for these four tests lie on the intersection of Curve C and the yield line, and in all cases the yield line on which the failure point lies is the one toward which the failure point would be expected to move if the initial residual stress (of the sign which was known to exist) was large enough to put the corresponding failure point beyond the yield line.

Fig. 3 shows an example of how the equilibrium value of residual stress can be predicted. For test No. 4, we assume that the initial residual stress was a large tensile value, and that fading has occurred such that the failure point F lies at the intersection of Curve C and the yield line. Now the loading line E representing $S_a = S_m$ can be drawn through F intersecting the abscissa at a predicted residual stress value of +8000 psi.

To summarize, 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.

The explanation of the measured notched fatigue limit values in Table XIV is now clear. In 61ST the yield lines intersect Curve C at abscissa values of considerable magnitude. Consequently, even after fading of initial residual stress has occurred, so that the failure point is on the yield line, there is considerable effect of residual stress. The effect is favorable if compressive and detrimental if tensile. Thus residual stress can change the fatigue strength of 61ST by as much as ± 35%.

For 61S-0, the yield line intersects Curve C essentially at zero mean stress. Consequently, regardless of their initial values, all residual stresses fade to approximately the same equilibrium values, and they have no effect on the fatigue strength.

For two reasons, it is to be expected that residual stress will be less effective in notched than in unnotched specimens. First, since K_t is larger than K_f , Curve C is higher than the unnotched curve. As a result, the intercept between the yield lines is shorter for Curve C than for the curve for the unnotched fatigue strength. This means that the effect of equilibrium residual stress is smaller in notched specimens than unnotched specimens. Second, for equal slopes of Curve C and the curve for unnotched fatigue strength, there is a greater percentage effect of equilibrium residual stress on the unnotched fatigue strength.

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. Percentagewise, 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 ratio, S_e/S_y. The build-up of residual stresses in 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% 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 tread 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.

GENERAL ELECTRIC COMPANY

100 x 140 - 7/100 in. div.

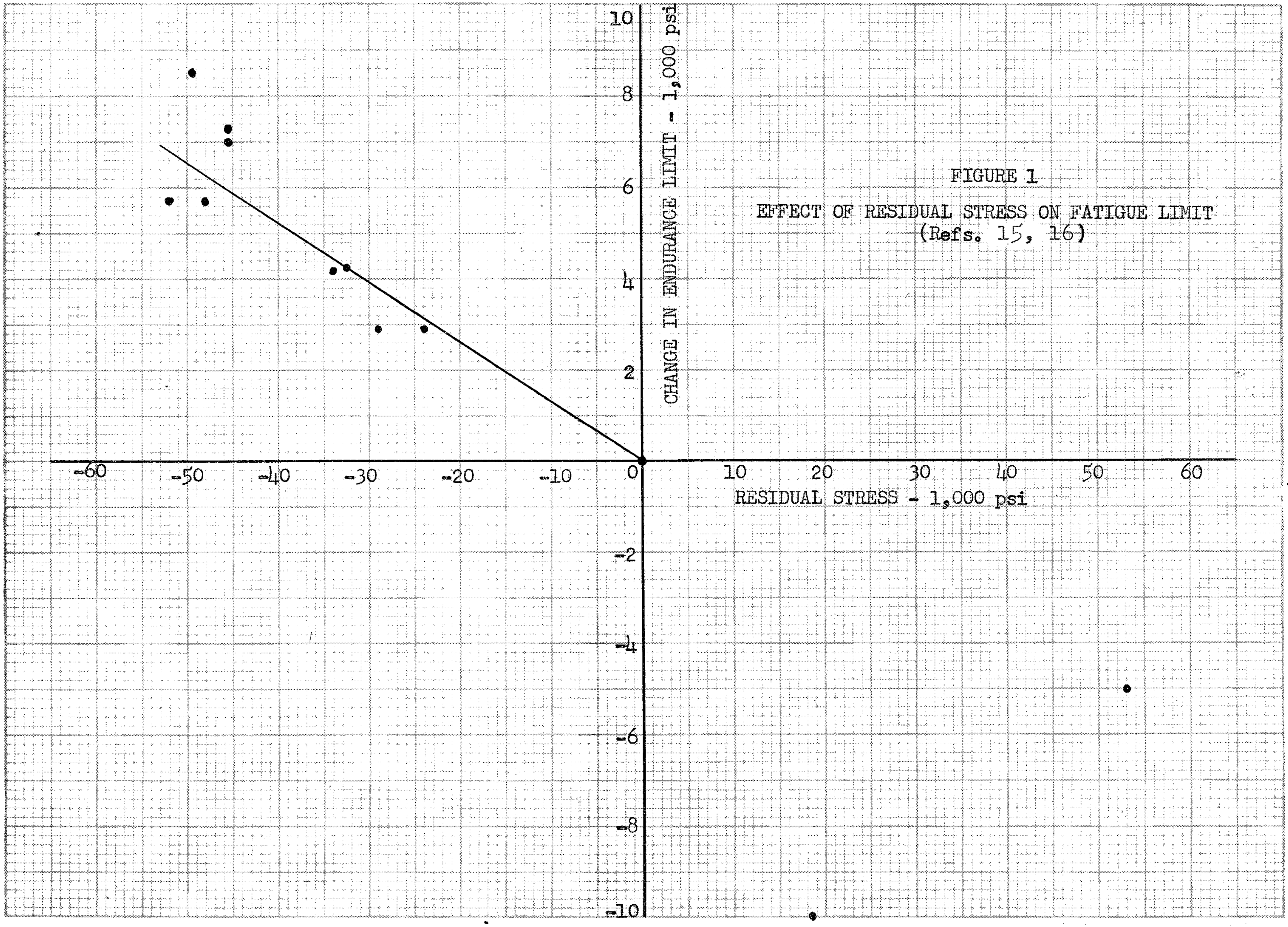
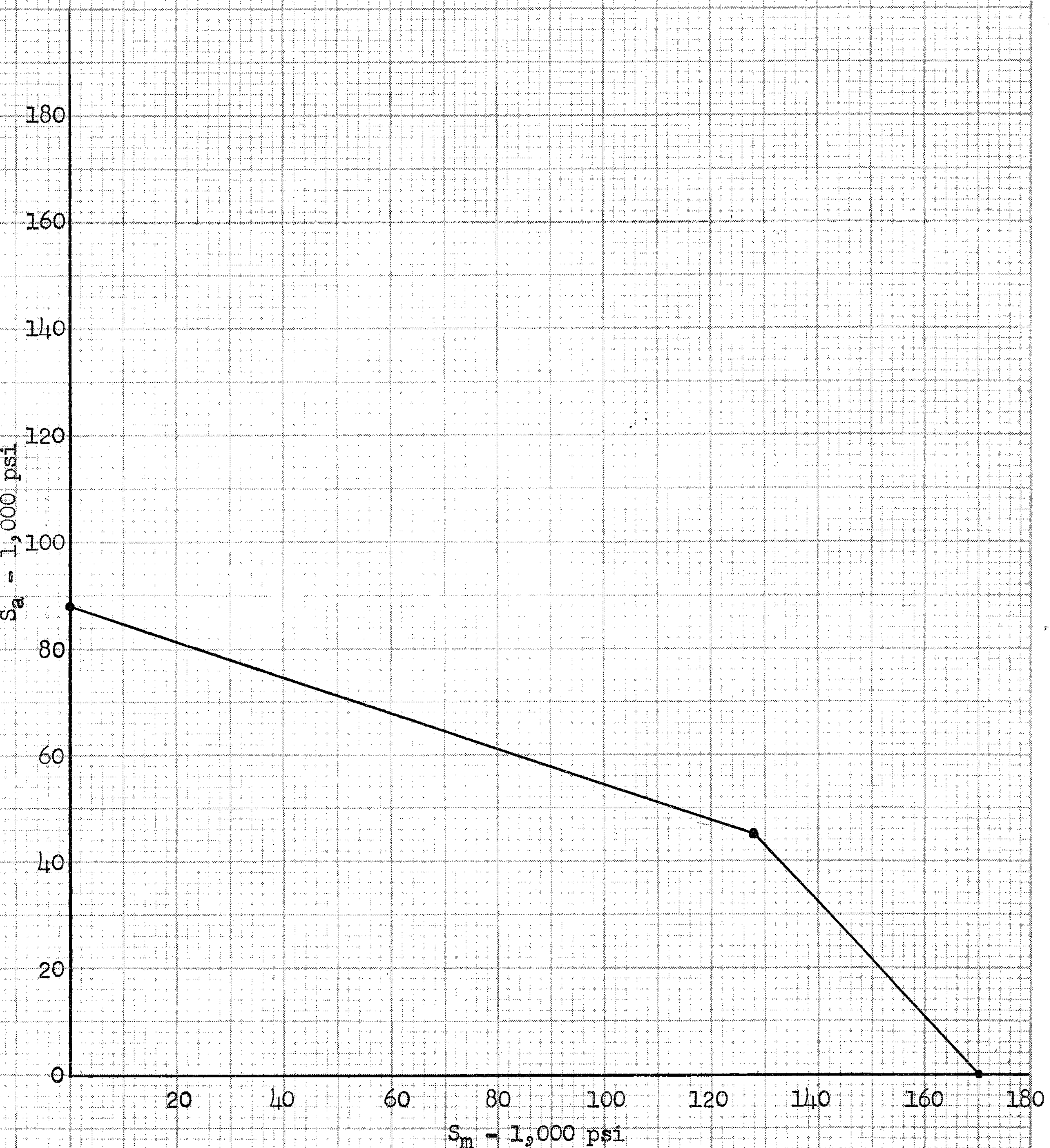


FIGURE 1

EFFECT OF RESIDUAL STRESS ON FATIGUE LIMIT
(Refs. 15, 16)

FIGURE 2

HAIGH-SODERBERG DIAGRAM FOR UNSTRAIGHTENED CRANKSHAFTS (Ref. 19)



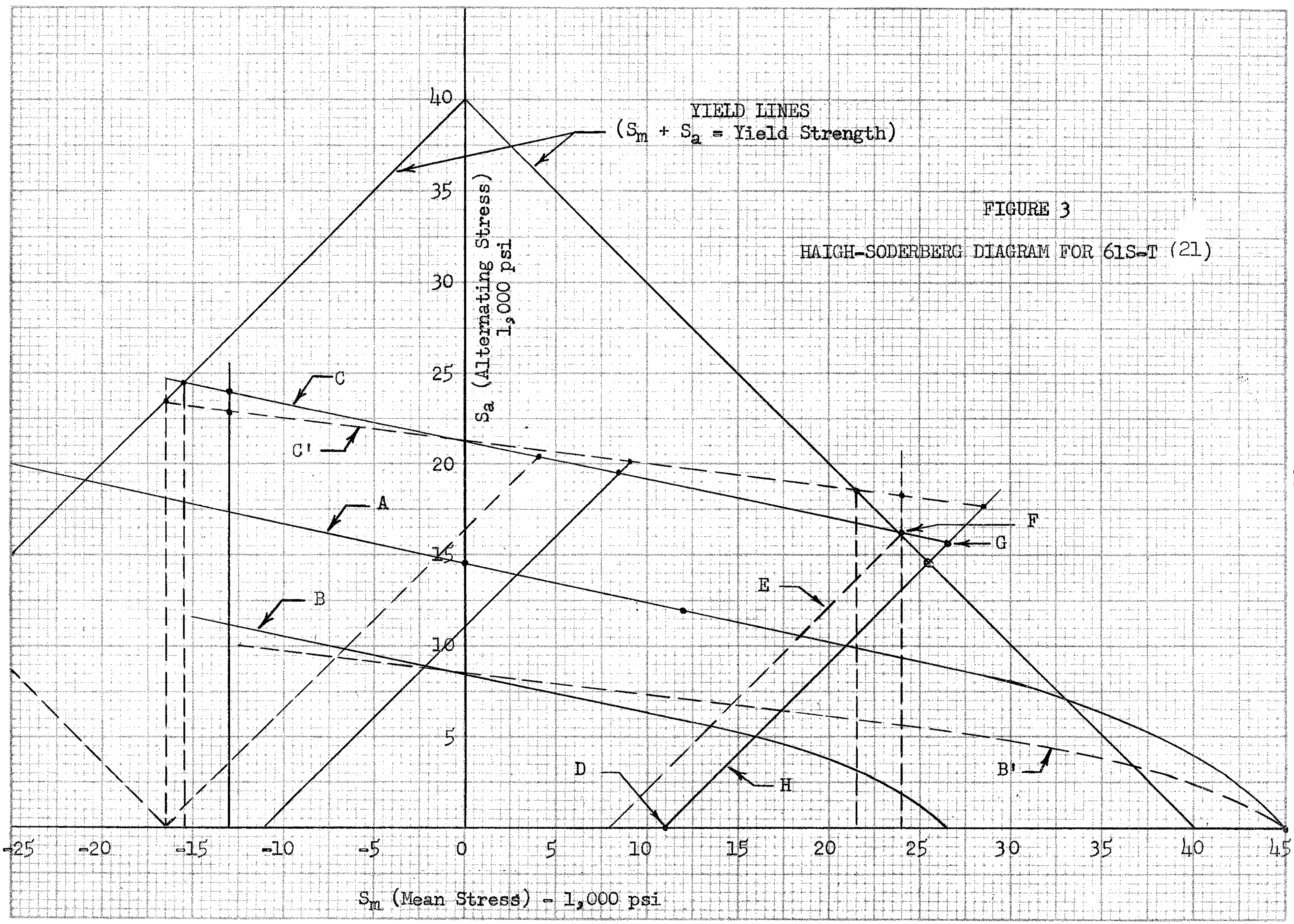


FIGURE 3
HAIGH-SODERBERG DIAGRAM FOR 61S-T (21)
YIELD LINES
(S_m + S_a = Yield Strength)
S_a (Alternating Stress)
1,000 psi
S_m (Mean Stress) - 1,000 psi
A
B
B'
C
C'
D
E
F
G
H
40
35
30
25
20
15
10
5
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
45

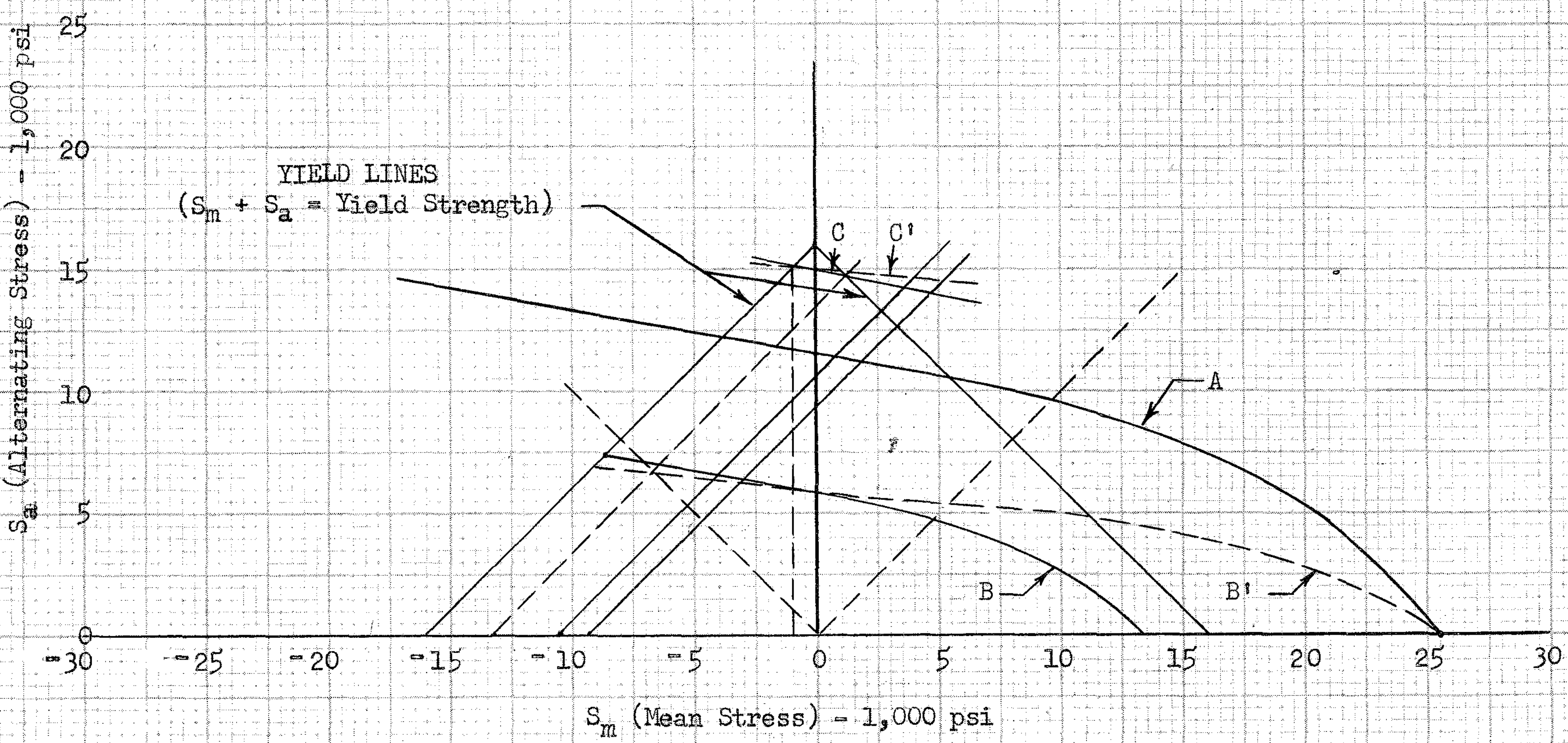
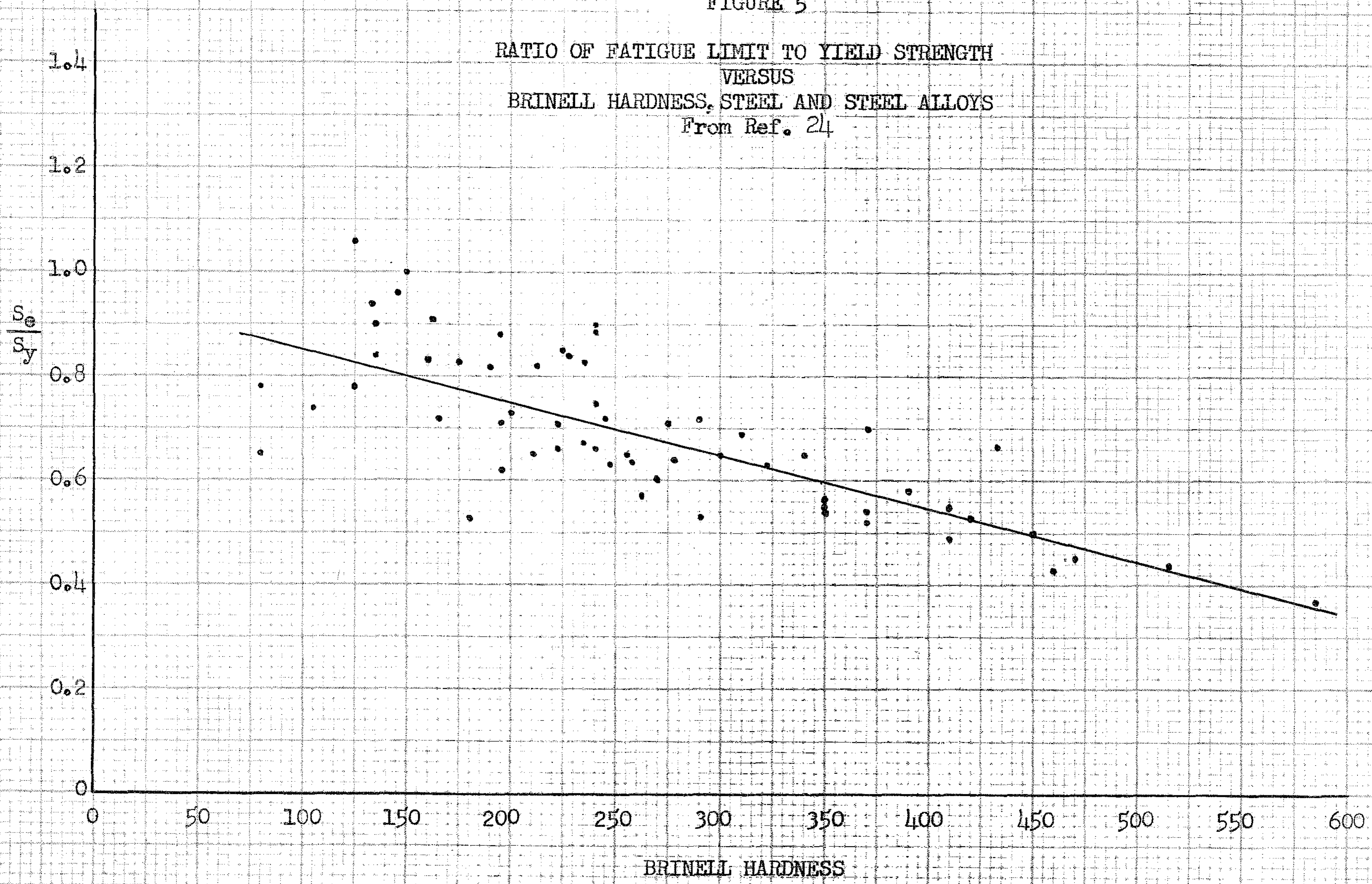


FIGURE 4

HAIGH-SODERBERG DIAGRAM 61S-0(21)

FIGURE 5

RATIO OF FATIGUE LIMIT TO YIELD STRENGTH
VERSUS
BRINELL HARDNESS, STEEL AND STEEL ALLOYS
From Ref. 24



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