THE EFFECTS OF SURFACE DISCONTINUITIES ON THE FATIGUE PROPERTIES OF CAST STEEL SECTIONS

A RESEARCH PROJECT AT CASE
INSTITUTE OF TECHNOLOGY

Sponsored by
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STEEL FOUNDRY RESEARCH FOUNDATION

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SCOPE OF THE RESEARCH REPORT

Studies have previously been published by the Foundation relative to test specimens produced in cast steel having various degrees of shrinkage porosity and tested in static loading. The effect that the discontinuities had on the properties of steel casting sections was presented.

The studies of this report are an extension of previous studies with the exception that the discontinuity containing specimens were dynamically loaded by testing in bending and torsion fatigue. These studies were primarily confined to the determination of surface discontinuities on the fatigue properties.

It was observed in the previous research that the shrinkage porosity must be very severe (Classes 5 and 6 ASTM E71 Reference Radiographs) before a decrease of 8 percent was observed in the strength of the cast steel sections. For this reason the discontinuities produced in the fatigue specimens were also severe.

The objectives of the research were to produce various types of surface discontinuities and to determine the effect of these discontinuities on the fatigue properties of cast steel sections with the hope that design and materials engineers will take a more realistic view of factual information and not rely so heavily on non-destructive interpretations.

SUMMARY OF THE RESEARCH REPORT CONCLUSIONS

The results of tests made on cast steel sections made under dynamic loading in bending fatigue and torsion fatigue provided significant information concerning the influence of severe surface discontinuities on the endurance limit properties of cast steel.

1. The fatigue strength in bending and torsion of low alloy cast steel is lowered by the presence of severe surface discontinuities. However, the severe discontinuities lowered the endurance strength and ratio to the same or less extent as the presence of notches in the standard (R. R. Moore) fatigue tests.

2. The surface discontinuities were of greater severity than permitted by ASTM E125 Reference photographs for magnetic particle indications on commercial steel castings.

3. The surface discontinuities present in cast steel were more damaging in reverse bending than in reverse torsion.

4. Cast steel was less notch sensitive in the normalized and tempered condition than in the quenched and tempered condition.

5. Severe discontinuities in welds in cast steel lower the endurance strength of the weld from 3 to 20 percent, depending on heat treatment condition and type of fatigue testing.

PREFACE TO THE RESEARCH REPORT

Design and materials engineers have very definite opinions on the importance of discontinuities in structures as revealed by non-destructive testing. This condition results from a general application of non-destructive testing to engineering structures and parts during the past 30 years. These opinions have not been based on correlative testing but they have been fostered through familiarity with the various classes of severity revealed by reference radiographs or reference photographs resulting from radiographic and magnetic particle testing.

It has been only during the last few years that a few engineers have considered that the radiographic and magnetic particle imperfections as registered by the reference documents are entirely out of proportion to their intrinsic value.

It is the desire of the steel casting industry, as well as other industries, to produce a quality product. However, the higher the degree of quality the more intense the processing requirements and the higher the end product costs. Extra quality beyond normal commercial standards is in most cases not necessary or required because of the lack of information on the importance and value that is placed on the various degrees of discontinuities as observed by non-destructive testing.

A previous research report by the Foundation dealt with the effect of shrinkage porosity on the mechanical properties of steel casting sections. The tests were made by static loading in bending and it was observed that the strength of steel casting sections was not significantly influenced (1.6 percent) by the presence of considerable shrinkage at or near the center of the section. Even when the extensive shrinkage is brought to the surface by machining and is positioned at the area of maximum tensile stress concentration in bending, the loss in strength is only about 20 percent when compared to a sound casting. Of course, such conditions are seldom acceptable even if the discontinuity was not in an area of maximum stress concentration.

The research also taught that tensile tests of radiographically sound steel casting sections having a strength of 114,000 psi decreased only 4.5 percent to 109,000 psi for sections of Class 2 ASTM E71 shrinkage. A decrease of 8 percent to 105,000 psi resulted for sections having Class 5 to 6 shrinkage. This fact is worth examining further. The steel of 114,000 psi tensile strength would undoubtedly be produced to ASTM A148 specification which requires 105,000 psi tensile strength. The designer would use the minimum value of the specification for his design value. The highest severity class in non-destructive testing would be applied if the design were based on specification minimum strength values. But this is not all - the designer then applies a factor of 2 because it is a ductile material, and then additional factors depending on his knowledge of the service loading, his familiarity with castings, and so on. These safety factors may add up from 3 1/2 to 10 far overshadowing any importance of the effect of a severe discontinuity. Yet in all probability the casting is ordered to Class 2 ASTM E71.

A reason given for the radiographic requirements despite the above facts was that the large percentage of steel castings produced are employed in dynamic loading service. Thus fatigue or impact testing would be a better criterion in the estimation of the relative importance of discontinuities and their effect on the properties of steel castings.

This need was met by setting up two research programs at Case Institute of Technology with testing of specimens cast to shape and of selected commercial castings in fatigue and impact loading. The studies of this report are concerned with the testing in bending fatigue and torsion fatigue of cast steel specimens containing surface discontinuities.

It is a well-known fact that surface notches have a pronounced effect on the endurance strength of metals and that surface discontinuities act as notches. The surface discontinuities employed in this research were gross and very severe; so severe, in fact, that they are beyond the reference radiograph and reference photograph (magnetic particle) classes. It was known before testing that these severe surface notches would have an effect on the endurance strength of the cast steel.

The research studies teach that the severe surface discontinuities in cast steel, greater than permitted in any class of commercial steel castings, do not reduce the endurance strength as much as results from the testing of the standard notched fatigue (R. R. Moore) test specimen. In fact, the Ni-Cr-Mo cast steel of these studies resulted in a 35 percent reduction in endurance strength when tested in fatigue by using the notched specimen. The surface discontinuity notches resulted in a reduction mostly of 8 to 20 percent.

Therefore, the notched fatigue endurance values of cast steel are good criteria for design and service requirements rather than severity classifications on the basis of non-destructive inspection employing reference photographs or radiographs to detail classes of severity. After all, severity classes have very little or no meaning for the successful design and application of the cast steel part.

The steel foundry companies through research and the technology which they are generating will continue their progress in the production of quality castings but unnecessary inspection requirements come high in terms of production costs.

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THE EFFECTS OF SURFACE DISCONTINUITIES ON THE FATIGUE PROPERTIES OF CAST STEEL SECTIONS

by

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THE EFFECTS OF SURFACE DISCONTINUITIES ON THE FATIGUE PROPERTIES OF CAST STEEL SECTIONS

Introduction

Investigations on the fracture by fatigue of metal parts have shown(1) that the number of repetitions of stress, rather than duration of time, is the main reason for causing failure of metals under relatively low stresses. Fatigue occurs only as a result of cyclic stressing with stress application applied very slowly, very rapidly, intermittently, or as a stress spectrum which is difficult to reproduce experimentally. These stresses may be caused by either vibrations, rotation, reciprocating motion of machine elements, alternate loading and unloading, thermal changes, magnetostriction, or otherwise. Nevertheless, irrespective of the source of cyclic stress, fatigue is the phenomenon of progressive fracture of metal by means of a crack which is propagated by repeated cycles of stress or strain. Fatigue is a discrete property of metals, and despite many attempts to prove otherwise, there is no correlation between fatigue and any other mechanical property(2).

Fatigue failures are a result of progressive strain hardening, particularly in areas of high stress concentration which can arise from part configuration and material discontinuities. The discontinuities include : non-metallic inclusions, cracks, cavities or porosity. Discontinuities at the surface of the steel part or casting often produce the areas of highest stress concentration. High stress concentration areas also result from design, environmental manufacturing of the material, or from fabrication, including : machining, grinding and polishing marks, screw threads, sharp or reentrant angles, keyways and oil grooves, drilled holes, press fits, cracks resulting from heat treatment, identification or inspection marks, weld defects, corrosion pits, eroded surface, etc.

Fatigue cracks in structural parts usually start at a fillet, groove, hole, rivet, or other irregularity in the section. It can be shown(3) from the theory of elasticity, that the peak stress near such a change in section is higher than the average or nominal stress in the surrounding neighborhood. Because of this, an appropriate name, “stress raiser” has been applied to such irregularities.

A measure of the severity of a stress concentration is given by the stress concentration factor, K_t, which is defined as the ratio of the maximum local stress in the region of the discontinuity to the nominal local stress, evaluated by simple theory. The nominal stress may be based either on the net cross section through the discontinuity or on the gross cross section of the member ignoring the discontinuity. The maximum local stress at the discontinuity may be determined mathematically, by photo-elasticity or by direct measurement of deformation.

Although fatigue strengths are considerably reduced by geometrical stress concentrations, the reduction is often less than the theoretical stress concentration factor, K_t, and a fatigue strength reduction factor, K_f, has, therefore, been introduced. This factor is defined as the ratio of the fatigue strength of a specimen with no stress concentration at N cycles, to the fatigue strength with stress concentration at N cycles. A measure of the degree of agreement between K_f and K_t is given by the notch sensitivity factor (q), which is defined as:

$$q = \frac{K_f - 1}{K_t - 1} \qquad (1)$$

The values of (q) lie between zero and one. When $K_f = K_t$, $q = 1$ and the material is said to be fully notch sensitive in fatigue. If the presence of a notch does not affect the fatigue strength, $K_f = 1$ and $q = 0$ and the material is notch insensitive. It is found(4,5)however, that the values of (q) depend not only on the material, but also on the stress condition, the size and shape(6) of the specimen or part, severity and type of notch, type and severity of loading, and the endurance, so that (q) cannot be regarded as a material constant.

A great many experiments have been carried out to determine the reduction in fatigue strength caused by the introduction of a notch, so that there is considerable information available on the relation between the stress concentration factor, K_t, and the fatigue strength reduction factor, K_f(7,8) Usually K_f is less than K_t and a number of factors contribute to this discrepancy.

Probably the most important factor affecting K_f is the size(9-13) of the notched part undergoing fatigue. However, fatigue strength is independent of size for plain specimens tested in direct stress, but increases with a decrease in size for plain specimens tested in bending or torsion and for notched specimens under all stress conditions. Size effect in fatigue is a serious factor because tests on small laboratory test pieces may indicate values of fatigue strength which are higher than can be withstood by large components in service. Wire has a higher fatigue strength than that of a standard test specimen (nominal 0.3 inch diameter). For sizes larger than the standard specimen, fatigue strength decreases approximately 15 percent up to 1/2 inch diameter; above 1/2 inch diameter and up to about 2 inch diameter, fatigue strength is only changed slightly. For parts above 2 inch diameter, the endurance strength may be reduced by 25 percent or more below the endurance limit of the standard test specimens(14). Thus, large specimens tend to have much lower endurance strengths but since large-scale testing is uneconomical, insufficient data are available for a firm generalization.

Only unnotched specimens tested in direct stress have the stress uniformly distributed over the test section. Therefore, it appears that size effect is a consequence of the limiting of the maximum stress to a small volume of material; the fatigue strength increases as the volume of material at the maximum stress is decreased or, to put it another way, the fatigue strength increases as the stress gradient is increased.

Two other important factors which have an effect on the notch fatigue strength are a mean stress superimposed on the alternating fatigue stress and the surface condition of the material. The addition of a static tensile stress reduces the fatigue strength of notched and unnotched material in both axial and bending fatigue, while the addition of a static compressive stress usually increases the fatigue strength. A steady static torque reduces the fatigue strength of notched specimens, while no reduction is observed in unnotched specimens.

Residual tensile stresses reduce the fatigue strength while residual compressive stresses increase the fatigue strength of materials(16-19). Several mechanical means of surface treatment can be employed to produce beneficial residual compressive stresses : cold working, tumbling, and shot-peening(19-21). These operations cold work or strain harden the material at the surface.

Fatigue failures almost always propagate from a free surface, so that the surface condition has a considerable effect on fatigue strength. This is because the stress is usually greatest at the surface, particularily when stress concentrations are present. There are basically three ways in which surface treatment influences fatigue strength : first, by affecting the intrinsic fatigue strength of the material near the surface, for example, by strain hardening ; second, by introducing or removing residual stresses in the surface layers; and third, by introducing or removing surface discontinuities which act as stress raisers in the surface.

Many of the different discontinuities can be eliminated by machining, or surface grinding, careful manufacturing and fabrication procedure, and by correct design practice. The effects of discontinuities can also be reduced by adding stress relieving notches in the vicinity of the stress concentrators.

Surface discontinuities such as porosity, slag or sand inclusions, weld defects, hot tears, etc., all reduce the fatigue strength of materials(22-27). The fatigue strength is not only affected by discontinuities, but also is affected by the type of manufacturing process. For example, unnotched, aligned structure wrought steel tested in the direction of rolling has been shown(28) to have better fatigue properties than equiaxed cast materials. However, tests made transverse to the direction of rolling result in lower fatigue strength values than for equiaxed cast steel.

Since many variables affect the fatigue strength of materials, experimental data for these materials with various kinds of discontinuities present under different loading conditions would be very useful information to the design engineer. With this information, a reasonable estimate of the fatigue life of the material with discontinuities can be made for actual loading conditions.

Therefore, the purpose of these research studies was to ascertain the effects of discontinuities on the fatigue strength of low alloy (Ni-Cr-Mo) (8630) cast steel at two different strength levels. Fatigue tests were performed on cast steel specimens of tensile strength between 80,000 and 90,000 and 120,000 and 145,000 psi containing various kinds of discontinuities in both reversed bending and reversed torsion.

Materials and Procedure

Casting Practice . . . A very popular grade of cast steel, a Ni-Cr-Mo (8630 type) was selected for the studies. The steel was melted in a basic lined furnace. Aluminum was employed for the final deoxidation by adding 0.06 percent aluminum to the pouring ladle. Nine different heats of steel were employed as shown in Table 1 and the tensile properties of the steels in the two heat treated conditions are shown in Table 2. The steel was cast into sand molds to produce bending fatigue specimens, torsional fatigue specimens and coupons from which tensile and R. R. Moore fatigue specimens were machined.

Production of Sound Bending and Torsional Fatigue Specimens . . . Bending and torsion fatigue specimens free of discontinuities were produced for control and comparison purposes. Keel block coupons were cast according to ASTM specifications A370 for test coupons and the tensile and R. R. Moore fatigue specimens machined from them were used to establish the mechanical and fatigue properties of the various heats.

The bending and torsion specimens were cast three to a mold employing a gating and risering system illustrated in Figures 1 and 2. A centrally located spherical Styrofoam riser with an exothermic core at the riser neck was used to expedite riser removal, decrease production costs, and assure efficient feeding of the test section. The torsion specimen was molded with semi-circular chills located adjacent to the reduced section (Figure 2) to insure optimum radiographic soundness in the central test section.

Fatigue Specimens With Surface Cavities . . . Gas cavities were produced in bending and torsional fatigue specimens by eliminating the aluminum as the final deoxidizer. Only ferro silicon was employed. Figure 3 illustrates the gas cavities obtained in the fatigue specimen castings.

TABLE 1

Chemical Analysis of Ni-Cr-Mo (8630) Cast Steels

Heat No.	%C	%Mn	%Si	%Cr	%Ni	%Mo	%P	%S	Acid Soluble AL(%)
1	0.33	0.84	0.31	0.45	0.55	0.25	0.018	0.03	....
2	0.31	0.81	0.22	0.34	0.39	0.26	0.013	0.29	....
3	0.32	0.83	0.32	0.45	0.55	0.20	....	....	0.23
4	0.30	0.82	0.29	0.45	0.55	0.20	0.028	0.032	0.045
5	0.30	0.79	0.19	0.36	0.40	0.15	0.014	0.030	....
6	0.34	0.90	0.28	0.54	0.70	0.25	....	....	0.07
7	0.25	0.62	0.15	0.46	0.40	0.15	0.023	0.029	0.09
8	0.34	0.85	0.30	0.45	0.55	0.20	....	....	0.05
9	0.32	0.58	0.21	0.48	0.51	0.10	0.038	0.033	....

Quench Cracks in Bending Fatigue Specimens . . . Quench cracks were produced by improper quenching practice of bending fatigue specimens and Figure 4 indicates the location and direction of the quench cracks obtained.

Hot Tears in Torsion and Bending Fatigue Specimens. . . Hot tears were produced by taking into consideration two principles: (1) differences in contraction of mold and casting, and (2) differences in time at which contraction occurs at different locations within the casting. Figures

TABLE 2

Tensile and Hardness Data for Steel Used

Heat No.	Heat Treatment*	Tensile Strength (psi)	Yield Strength (0.2% offset, psi)	Reduction in Area (%)	Elongation (1.4 inch gage length %)	Brinell Hardness No.	Type of of Specimen
1	Q T	132,000	117,000	28.4	11.4	285	Hot Tears
1	N T	87,300	56,800	32.7	20.3	170	Hot Tears R.R. Moore-Notched R.R. Moore-Unnotched
2	Q T	126,000	111,100	36.2	13.7	382	Cavities
2	N T	82,300	50,400	25.8	48.0	162	Cavities
3	Q T	126,000	110,000	44.2	16.1	274	R.R. Moore-Notched R.R. Moore-Unnotched Weld
3	N T	88,300	60,800	46.3	22.1	184	Weld
4	Q T	122,000	108,400	32.7	14.2	262	Weld
4	N T	89,800	62,300	43.2	20.4	186	Weld Hot Tear
5	Q T	124,100	110,800	34.4	15.3	265	Weld
5	N T	90,200	62,600	47.5	22.9	187	Weld
6	Q T	137,000	125,600	32.6	16.1	285	Quench - Cracks
6	Q T	145,000	128,000	32.9	12.1	321	Sound
7	N T	83,100	52,800	35.1	21.4	167	Sound
8	Q T	128,000	113,000	37.0	13.9	285	Hot Tear
9	N T	88,900	49,300	33.8	19.6	173	Slag Inclusion

* Q T = Quenched and Tempered
N T = Normalized and Tempered

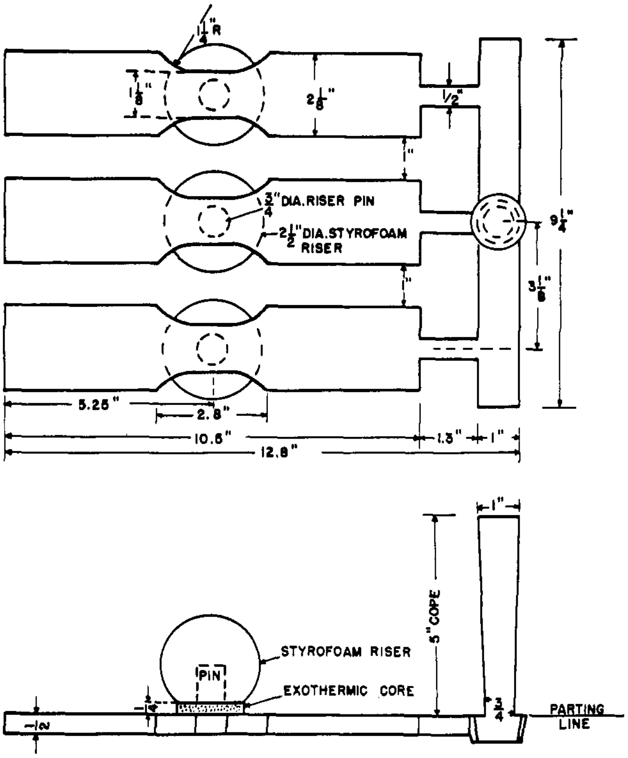


Figure 1—Gating and Risering Arrangement for Bending Fatigue Specimens.

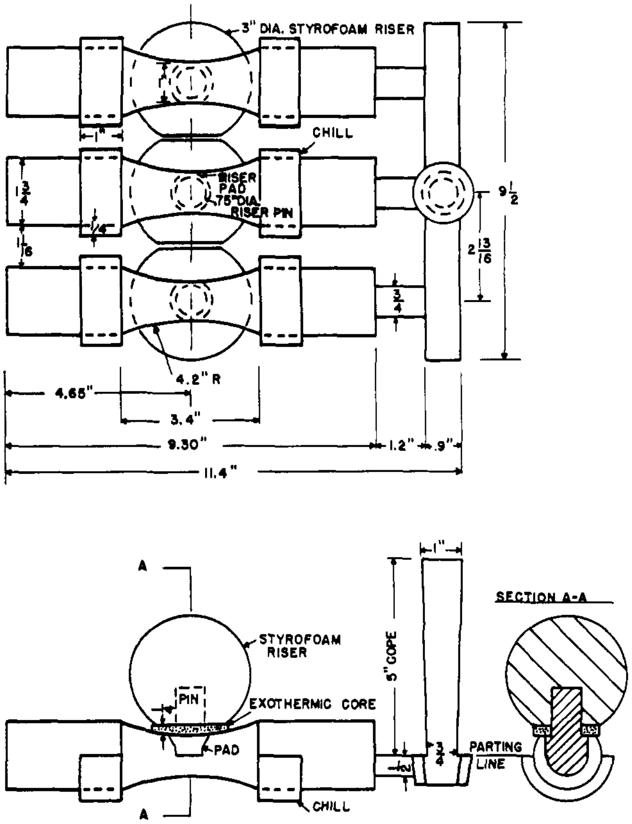


Figure 2—Gating and Risering Arrangement for Torsion Fatigue Specimen Castings.

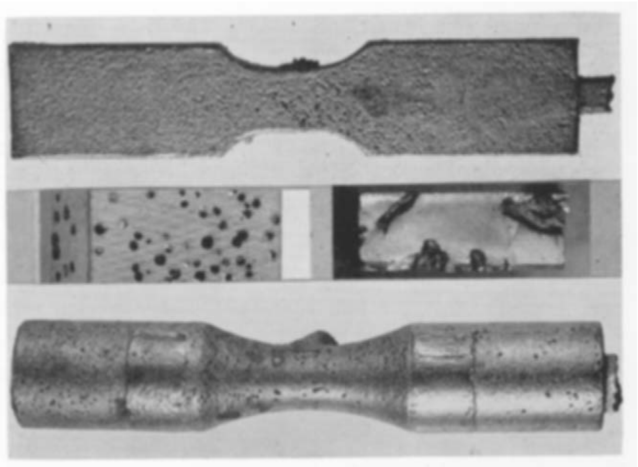


Figure 3—Illustrates Cavities in Bending and Torsion Fatigue Specimens.

5a and b demonstrate the method used to produce hot tear discontinuities.

The riser over the center of the bending and torsion test section not only feeds the test section to radiographic soundness, but also causes a hot spot or weak zone of stress concentration where the hot tears take place when the casting is restrained from contracting by chill application and the protruding cast-in wedges.

The chills, whose dimensions were three and one-half inches long by one inch wide by one-quarter of an inch thick, were placed in the drag portion of the mold. Upon removing the pattern, small wedge shaped cavities, shown in Figure 5, were cut into the sand mold on either side of the chills. These cavities became part of the casting and restrained the casting from free solidification and cooling contraction by pressing against the chills. This situation was further aggravated

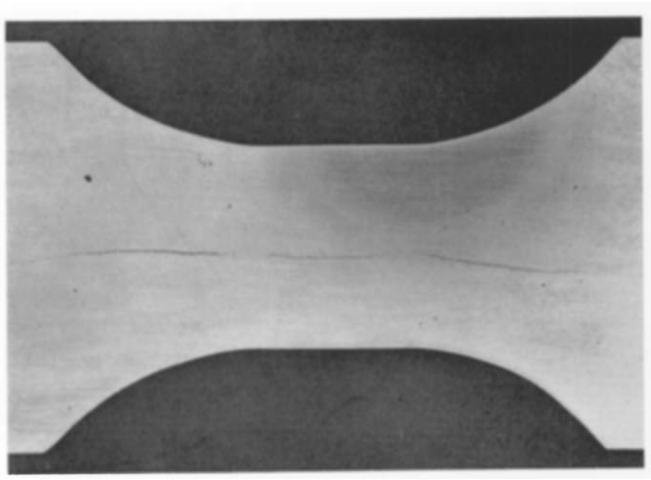
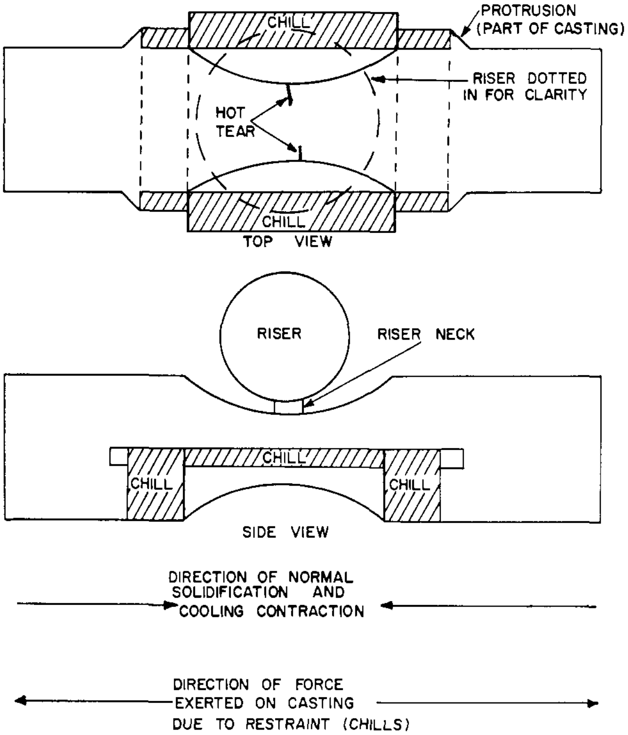
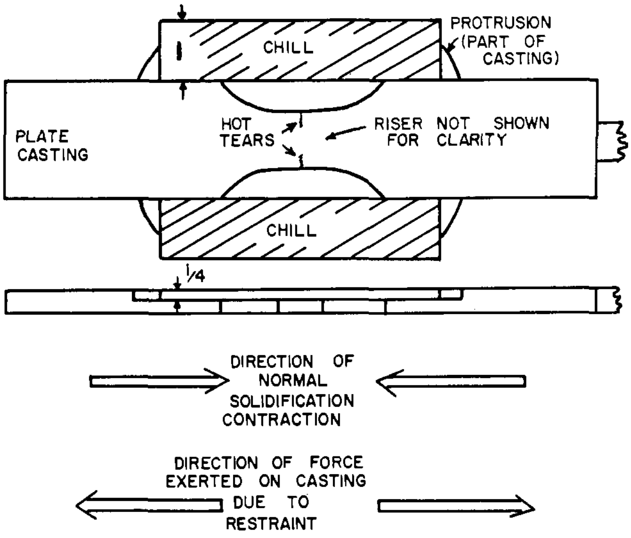


Figure 4—Indicates the Direction and Location of Quench Cracks in Bending Fatigue Specimens.



a. Torsion Fatigue Specimen.



b. Bending Fatigue Specimen.

Figure 5—Schematic Representation (not to scale) of Method Used to Produce Hot Tears in Fatigue Specimens.

by the expansion of the chills on heating. The severity of the hot tears increased with chill length such that chills over eight inches in length ruptured the castings in half. The actual chill lengths used for producing the test bars ranged from three to five inches. All test bars were magnetic particle inspected as a means of selecting test specimens.

All hot tears were produced perpendicular to the longitudinal axis of the bending and torsion specimens. The severity of the hot tear was determined by both visual and magnetic particle inspection and was used as a means of selecting test specimens. Figure 6 shows the as-cast torsion specimen with a hot tear present.

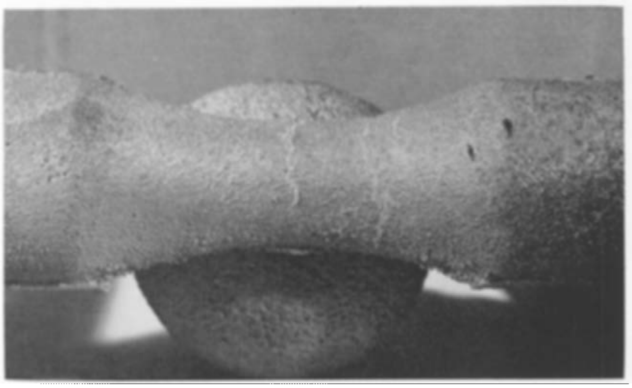


Figure 6—Magnetic Particle Powder Outlining a Hot Tear in the Torsion Fatigue Specimen.

Production of Specimens With Surface Slag Inclusions . . . Large surface slag inclusions in both the plate bending and torsion fatigue specimens were made by imbedding slag particles partially into the drag surface of the mold cavity. The slag used was a hard silicate by-product of a normal heat, crushed and screened to a sieve size of - 6 to +8 mesh. Most of the particles were not dislodged during pouring and became firmly imbedded in the specimen surfaces. Figure 7 illustrates the appearance of the slag bearing surfaces in the as-cast test bars.

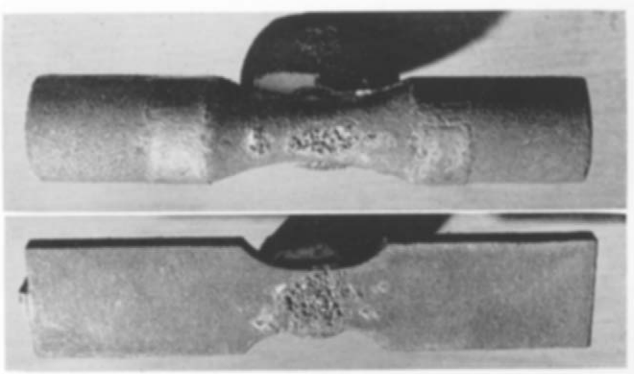
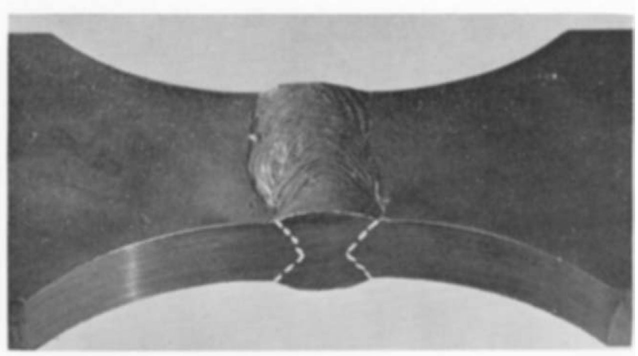
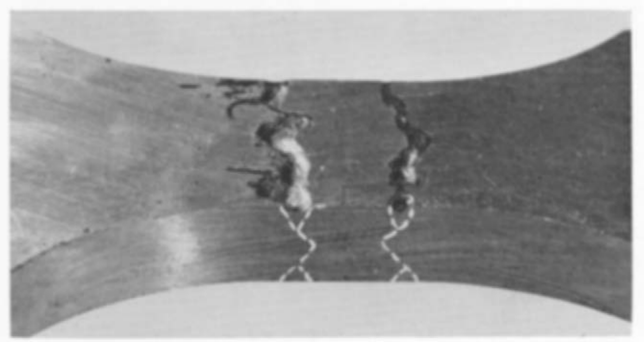
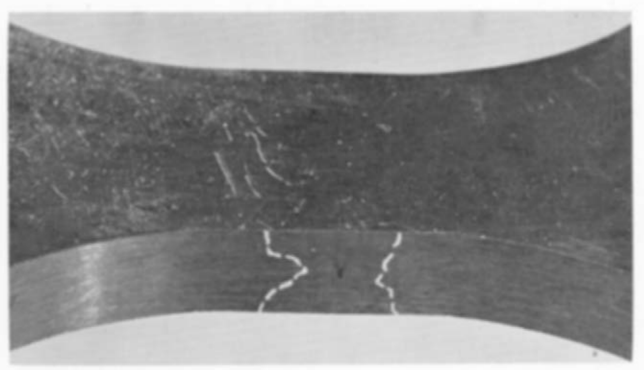


Figure 7—Surface Slag Inclusions in Cast Torsion and Bending Fatigue Specimens.

Welding Procedure . . . The bending and torsion fatigue cast steel specimens were welded by a commercial welding company in their as-cast condition. The types of weld discontinuities investigated were (1) sound weld, (2) sound weld with the reinforcing bead removed by machining, (3) weld undercut after machining, (4) weld slag inclusions after machining, and (5) weld incomplete penetration after machining. Figure 8 shows photographs of the different weld discontinuities in the bending fatigue specimens with a dotted line denoting the position of the weld.


a. Sound As Welded Specimen.


b. Weld Undercut Specimen.


c. Weld Slag Inclusion Specimen.

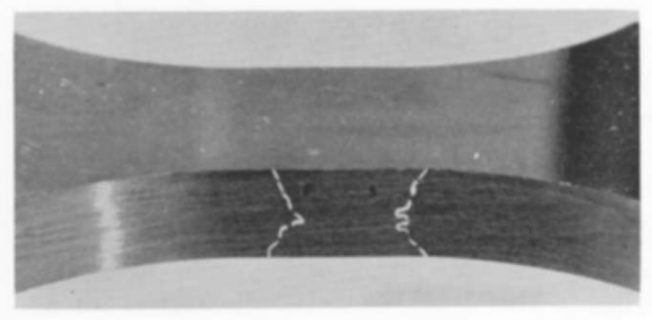

d. Weld Incomplete Penetration Specimen.

Figure 8—Bending Fatigue Specimens of Cast Ni-Cr-Mo Steel.

A double vee butt weld joint was employed since the fatigue specimens were to be tested in both reversed bending and reversed torsion. In this manner the weld discontinuity would be present on both sides of the specimen, and eliminate the strengthening effect caused by sound weld metal near one of the surfaces. The joint design for both bending and torsion specimens is shown in Figure 9. Two different procedures were employed in the preparation of the torsion specimens.

The welding electrodes used were of Hobart Type LH918M and were selected because the mechanical properties obtained upon heat treatment were compatible with the desired strength level of the specimens. A preheat temperature of 300 degrees F was used to produce slow cooling and a postheat temperature of 1100 degrees F, for one hour, was applied immediately to the completed weld to retard cooling and prevent the formation of underbead cracks.

Inspection of Material . , . All specimens were inspected by magnetic particle and radiographic examination and compared against ASTM reference standards for severity of the discontinuities. Table 3 indicates the reference document and class. It will be observed from the table that the discontinuities were so severe that they were unacceptable for any class of commercial steel castings. *

The weld-undercut specimens contained discontinuities which did not come to the surface of the specimens after they had been machined. However, magnetic particle inspection did show that the discontinuities were located under the surface. The weld-undercut discontinuities have been included as a part of the surface discontinuities because it was advisable to keep all the welding of cast steel studies together as a group and to classify them as surface discontinuities. The weld bead on the sound welded cast steel specimens certainly acts as a position of stress concentration rather than a discontinuity.

Heat Treatment of Material . . . The tensile strength levels selected were 80,000 to 90,000 psi and 120,000 to 145,000 psi. These levels were ob-

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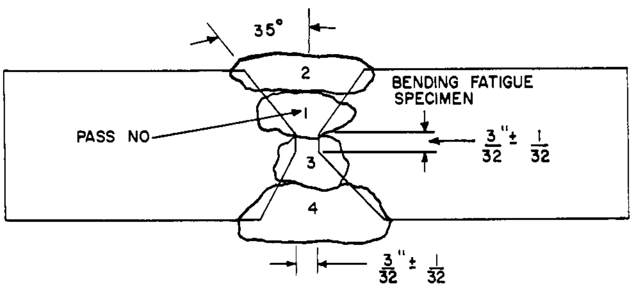
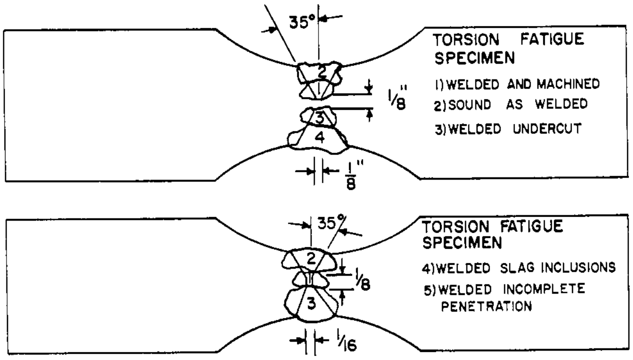
* Minimum Standards for Commercial Steel Castings produced to no non-destructive tests require that the castings be of no lower quality than Class 4 ASTM E71. The discontinuities in the test specimens were in all cases so severe that they exceeded the acceptability of all casting classes and if they appeared in commercial steel castings, the castings would be scrapped.



a. Bending Fatigue Specimen.



b. Torsion Fatigue Specimen.

Figure 9—Sketch of Weld Joint Design (not to scale) for Fatigue Specimens.

tained by two heat treatments : (1) normalize and temper and (2) water quench and temper. Specimens were water quenched from the tempering temperature. The specimens tested with the weld bead in place were heat treated under a protective neutral atmosphere to avoid decarburization. The other weld specimens were heat treated in gas fired furnaces. All the other specimens containing gas cavities, hot tears, surface slag inclusions and quench cracks were austenitized in salt pots prior to quenching; the tempering was conducted in electric resistance heated furnaces.

Machining.. . The bending fatigue specimens were machined to the dimensions illustrated in Figure 10a. The surface finish was from 4 to 10 microinches as determined by a profilometer.

The torsion specimens were machined and ground to the dimensions shown in Figure 10b. The surface finish of the test section was approximately 10 to 20 microinches after final grinding.

R. R. Moore fatigue specimens having the dimensions shown in Figure 11 were machined from keel block coupons.

Mechanical Testing . . . Average tensile test values of two strength levels (80,000 to 90,000 psi and 120,000 to 145,000 psi ultimate tensile strength) are tabulated in Table 2.

TABLE 3

ASTM Classification of Discontinuities in Fatigue Specimens

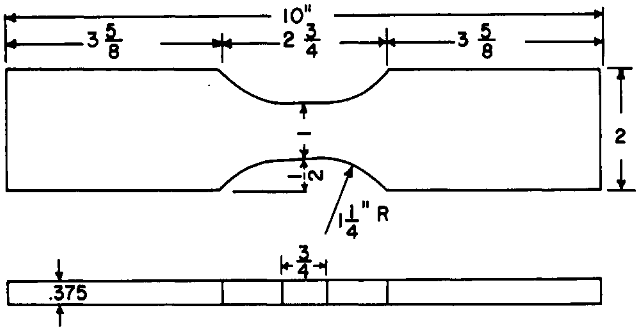
Type of Fatigue Specimen	Discontinuity	Severity (ASTM Classification)	Un-acceptable for Casting or Weld Classes
Bending	Weld - Incomplete Penetration	5-D(E99-55T) VI-2(E125-56T)	1 through 4
Bending	Weld - Slag	3-D(E99-55T) VI-4(E125-56T)	1 through 4
Bending	Weld - Undercut	9-E(E99-55T) VI-3(E125-56T)	1 through 5
Bending	Hot Tears	D-3(E71-64) I-4 to 5(E125-56T)	1 through 5
Torsion	Hot Tears	D-3(E71-64) I-4 to 5(E125-56T)	1 through 5
Bending	Cavities	A-6(E71-64) V-2(E125-56T)	1 through 5
Bending	Quench-Cracks	E-3(E71-64) I-5(E125-56T)	1 through 5
Torsion & Bending	Slag Inclusions	B-6(E71-64) III-5(E125-56T)	1 through 5

E71, ASTM	Reference Radiographs for Steel Castings up to 2 inch Thickness.
E99, ASTM	Reference Radiographs for Steel Welds.
E125, ASTM	Reference Photographs for Magnetic Particle Indications on Ferrous Castings.

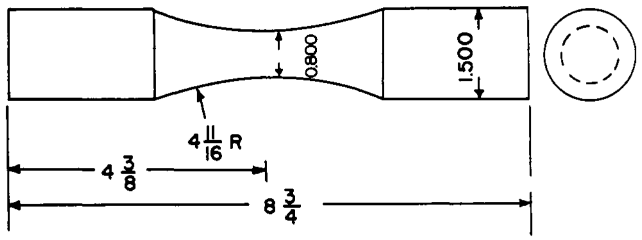
Fatigue testing was conducted on two types of machines: R. R. Moore specimens were tested in four point reversed bending on standard R. R. Moore machines operating at 10,000 cycles per minute. Bending and torsion fatigue specimens were tested on Sonntag SF-1-U constant load machines at 1800 cycles per minute. The bending specimens were tested in four point reversed bending in the fixture shown in Figure 12a. The test arrangement showing the lever arm connecting the vibrating platen which transmitted the torque to collets gripping the torsion specimen is illustrated in Figure 12b.

The bending specimens were considered to have failed in fatigue when they fractured completely. The torsion test equipment contained switches which discontinued fatigue testing when the machine amplitude capacity was exceeded and this condition was considered to constitute fatigue failure.

The fatigue tests were carried out at different stresses to obtain curves of stress versus number of cycles to failure. The number of specimens



a) PLATE BENDING FATIGUE SPECIMEN



b) TORSION FATIGUE SPECIMEN

Figure 10—Dimensions of the Bending and Torsion Fatigue Specimens.

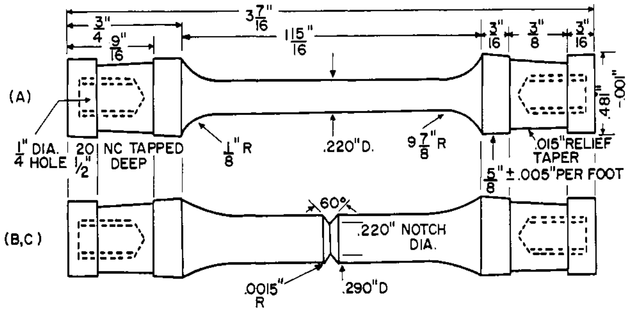


Figure 11—R. R. Moore Fatigue Specimen.

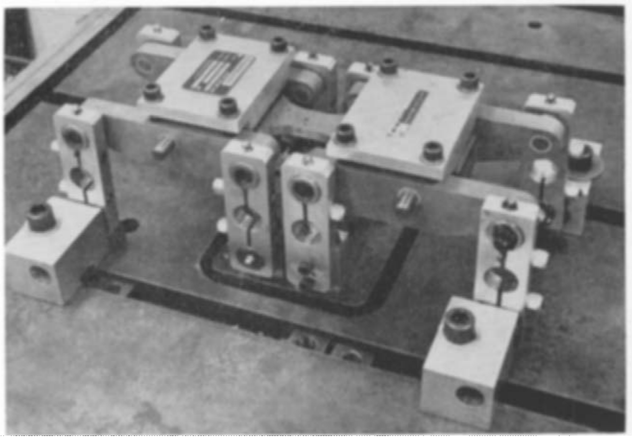
used for the S-N curves varied from seven to twelve. The endurance limit was based on ten million cycles. Specimens which exceeded the endurance limit were considered to possess infinite life.

Microstructure Influences on Fatigue

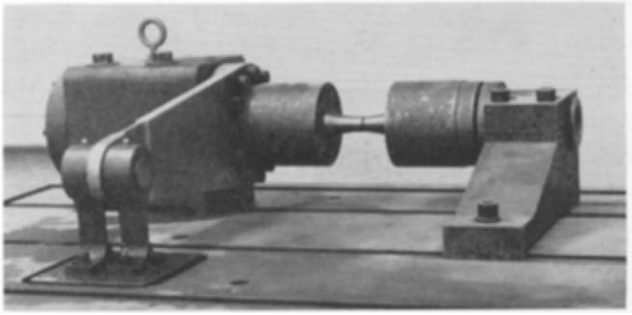
Microstructure influences the fatigue behavior of materials, thus photomicrographs were made of the areas adjacent to discontinuities to disclose any difference in the microstructure in this area, as compared to sound material. A structure consisting wholly of ferrite often has a fatigue limit greater than half its tensile strength, but the strength is low. The best fatigue properties for higher strength steels are obtained with tempered martensite. For example, Dolan and Yen(30) compared the fatigue strengths of a martensitic type of structure to that produced by slow quench. Tests were made on a carbon steel and two alloy steels, that were all tempered to about the same tensile strength. The endurance ratios for the tempered martensite were consistently above those for the mixed structure, by 5 to 9 percent for unnotched specimens and 1 to 14 percent for notched specimens.

The typical microstructure for steel in the as-welded condition is that of columnar grains in the weld metal and coarse grains in the heat affected zone blending into the structure of the steel casting. One of the benefits of heat treating completed weldments is the development of a more homogeneous structure across the joint. Heat treatment tends to erase the heat-affected zone ,and produce a more uniform microstructure. Figures 13a and b show that the columnar weld metal structure has been replaced by a uniform grain structure while the heat-affected zone has been replaced by a fine grain structure. This condition is apparent in the normalized and tempered material where the heat-affected zone is almost eliminated.

There is much evidence in the literature(31-34) concerned with the detrimental effect produced on fatigue behavior of material because of decarburization. For instance, Hankins(34) has shown the



a. Bending Fatigue Specimens.



b. Torsion Fatigue Specimens.

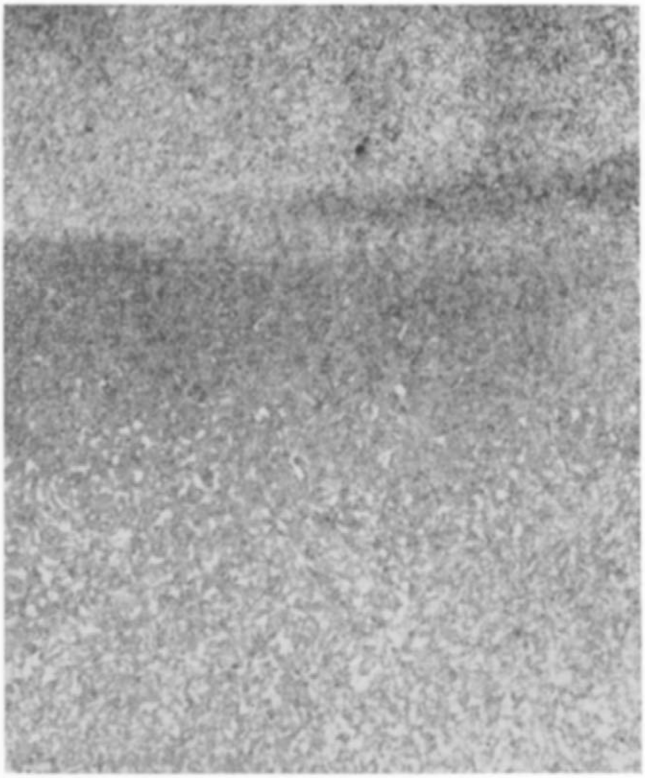
Figure 12—Illustrates Test Fixture Employed for Fatigue Testing.

effect of decarburization on spring steels. He found a reduction in rotating bending fatigue strength of 33 percent for low tensile strength spring steels to 90 percent for higher tensile strength spring steels. This form of discontinuity can be produced by any oxidizing atmosphere which may come in contact with the material at higher temperatures (+ 1250°F). A soft layer of low strength ferrite results with an embrittling oxide penetration between the grain boundaries, producing residual tensile stresses in the surface and increasing surface roughness, thus constituting a discontinuity in the material.

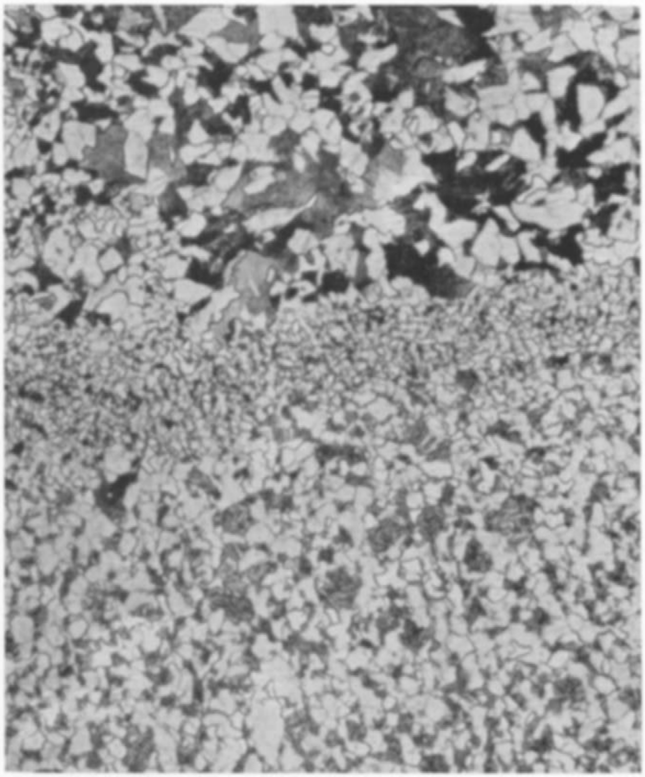
Figure 14 illustrates the decarburized layer adjacent to the weld with incomplete penetration. The average depth of the carburized zone was found to be approximately 0.0075 inch. Evidence(31)is available that indicates it is the presence and not the depth of the decarburized layer that causes the reduction in fatigue strength. Other specimens in which decarburization was found were hot tears, weld undercut, and cavities as these discontinuities were exposed during heat treatment to the furnace atmosphere.

Appearance and Locations of Fatigue Fractures

If a component is repeatedly subjected to loads of sufficient magnitude, a fatigue crack or cracks will eventually be formed in some highly stressed region, usually at the surface, and will gradually



a. Quenched and Tempered.



b. Normalized and Tempered.

Figure 13—Microstructures of the Quenched and Tempered and Normalized and Tempered Ni-Cr-Mo Cast Steel Showing the Cast Metal, Heat Affected Zone and Weld Metal. 500X Etched.

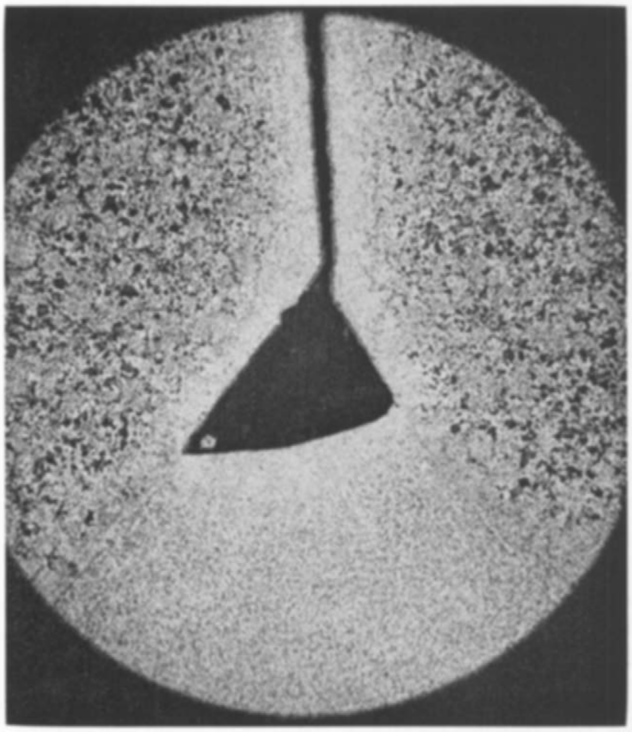
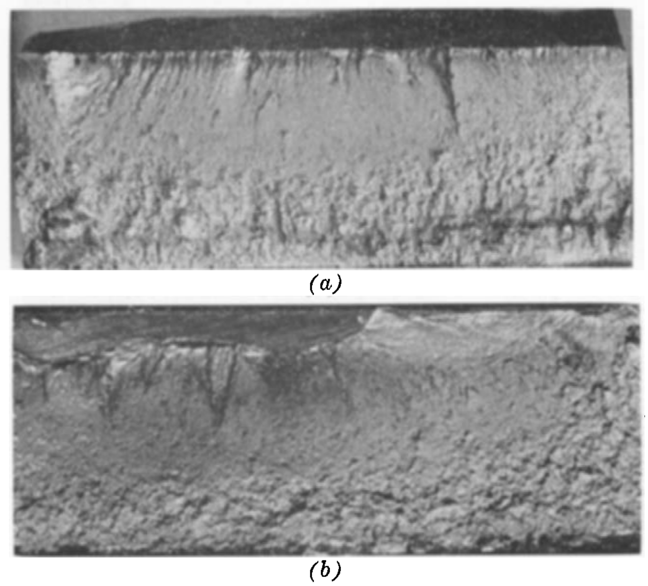


Figure 14—Decarburization in Casting and Weld Adjacent to Incomplete Penetration. 50X Etched.

progress through the metal until complete fracture results. The fractured surfaces of parts that have failed by fatigue generally have a characteristic appearance by which they may be recognized.

There are usually two or three zones which can be identified on each fractured surface from a macroscopic appearance. Around the origin of the crack, the surface often has a smooth appearance showing conchoidal or beach markings; that is, the area over which the fatigue crack has spread relatively slowly. A second, less smooth zone can sometimes be distinguished across which the crack has extended more rapidly, perhaps in several places at once, so that the fracture surface is irregular. The third zone may have either a crystalline appearance indicating that the final fracture has occurred in a brittle manner, or a fibrous appearance indicating a final ductile fracture.

In reversed plane bending, the straining action is confined to a single plane, but occurs first in one direction and then in the opposite direction. The simultaneous appearance of cracks on each side of the specimen without discontinuities is sometimes observed. The zone of final fracture then occupies a position at the middle of the broken section. For specimens containing discontinuities, fatigue cracks start in the areas of stress concentration and propagate across the section where final fracture takes place. Figure 15 illustrates weld discontinuities in which the fatigue crack has propagated across the section from one surface location. In some cases where discontinuities such as cracks are located within the material close to the surface, fatigue cracks can be initiated at these locations and propagate to the surface. This is easily understood since Neuber(3) has pointed out that an increase of as much as eight times the normal stress can be developed at the edge of an internal crack under a bending stress, depending on its length and root radius of the crack.



(a)

(b)

Figure 15—(a) Fractured Surface of Sound As Welded and (b) Welded Undercut Bending Fatigue Specimens. The Fatigue Crack Has Propagated Across the Section From One Surface Location.

The appearance of fatigue cracks caused by alternating torsion are different from those resulting from bending. Torsional fatigue failures occur in one of two ways: (1) along planes of maximum shear or (2) along planes of maximum tension. The maximum shear stress acts parallel, or at right angles, to the axis of the specimen, while the maximum tensile stress acts at 45 degree angles to the two shear stresses; for pure torsion, both these stresses are equal. Thus, there are two modes of torsional failure: (1) longitudinal or transverse, along planes of maximum shear and (2) helical, at 45 degrees to the specimen axis, along the plane of maximum tension. If the Maxwell-VonMises failure criterion is assumed, then the shear strength is 0.58 that of the tensile strength, and thus the shear stress will reach the shear strength before the tensile stress can attain the tensile strength.

It can then be concluded that if the fatigue limit is exceeded and there are no discontinuities, a fatigue crack will develop on the shear plane. However, the crack once formed results in a stress concentration and may cause the fracture to continue on a tensile plane.

The failure mode is usually tensile fracture if discontinuities are present. Tensile fracture occurs because the tensile stress is increased by the discontinuity while the shear stress remains relatively unchanged. Fatigue failure under tensile stress occurred in the specimens containing cavities, welded slag inclusions, and hot tears. Both the welded undercut and the sound weld specimens tested in torsion fatigue failed in shear (Figure 16). At first, this seems contradictory in the case of the weld undercut specimen since it contained a circumferential notch. However, Neuber(3) showed that for the size and root radius of the notch present in the weld undercut, the maximum shear stress is only increased by a small amount.

Fatigue failures in transverse butt-welded connections are usually initiated in the heat-affected zone or in the weld metal. Failures located in the heat-affected zone are influenced by the severity of the stress raisers at the edge of the weld. For example, all the machined, sound, and undercut weld

Figure 16—Illustrates Fatigue Crack and Fractured Surface of Sound Weld Torsion Fatigue Cast Steel Specimen.

specimens failed in this region. Failures in the weld metal are initiated from internal weld flaws, such as severe porosity, slag inclusions, and incomplete penetration. All welded specimens containing slag inclusions and incomplete penetration failed through the weld metal at the discontinuity. All fatigue failures in the porosity specimens initiated at a pinhole and progressed from one pinhole to the next to final failure.

A typical fracture which occurred in all the quench cracked specimens is illustrated in Figure 17. Note how the crack propagated across the specimen to the location of a quench crack and then was arrested, only to continue on a parallel plane which was offset from the first.

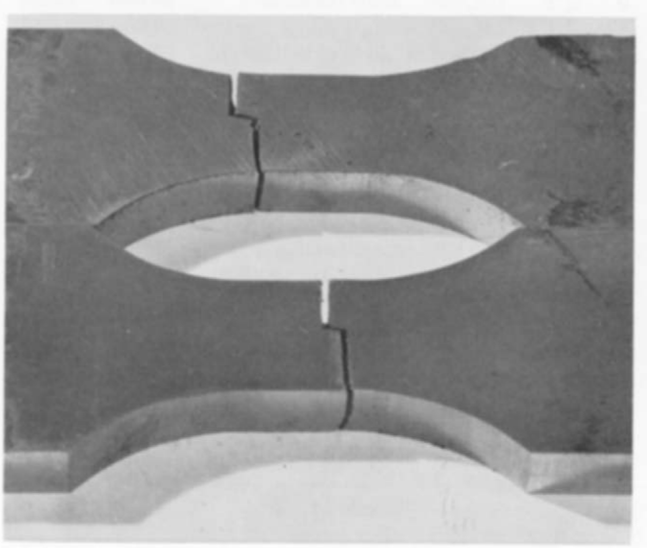
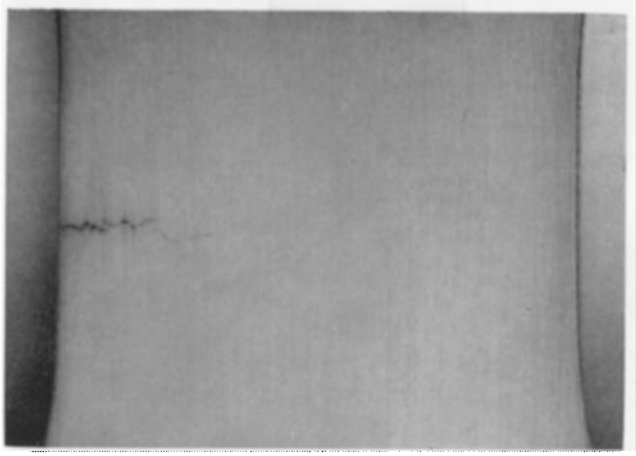
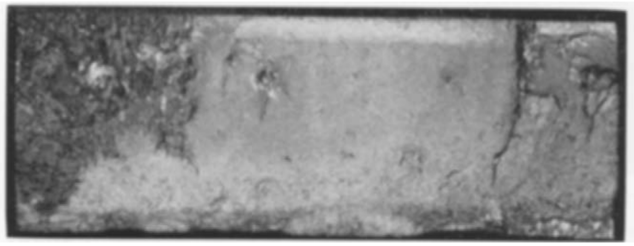


Figure 17—Fatigue Fracture of Quench-Cracked Bending Fatigue Cast Steel Specimen.

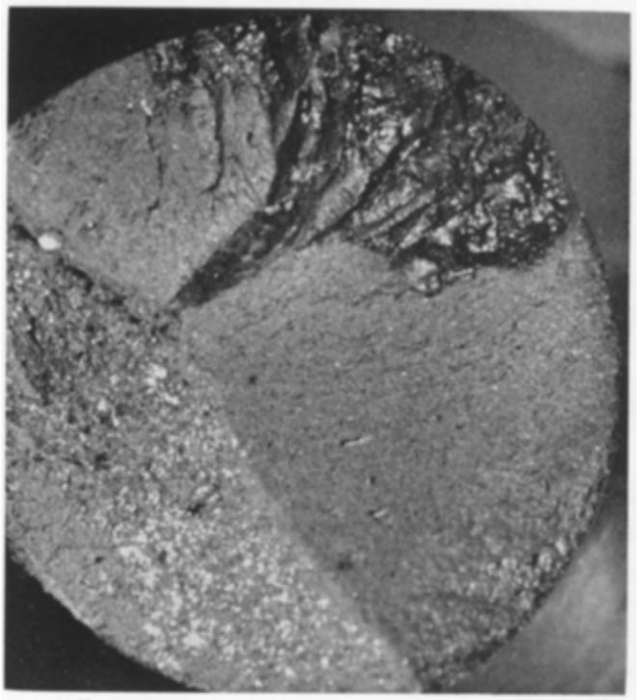
The surface of an unbroken hot tear containing test piece appears in Figure 18a while Figures 18b and c show the fracture surface of specimens with hot tears. The dark oxidized surface of the tear shows a dendritic structure indicative of the interdendritic nature of the hot tearing process,



a. Surface of Specimen.



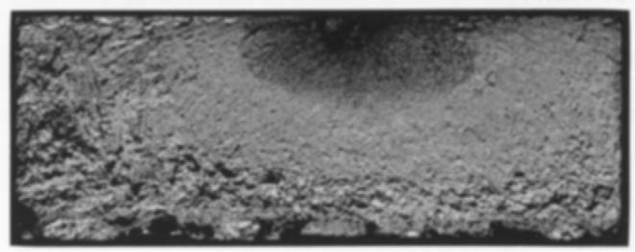
b. Fracture Surface.



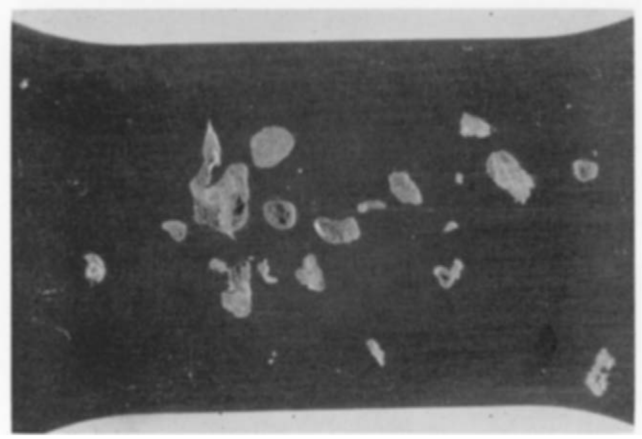
c. Fracture of Torsion Fatigue Specimen Showing Location, Size and Shape of Hot Tear Discontinuity.

Figure 18—Appearance of Hot Tear in Surface of an Unbroken Plate Bending Fatigue Specimen and a Fracture Surface Showing the Oxidized Hot Torn Region; (a and b are not from same test piece).

A fatigue fracture of one of the bars containing slag inclusions and a surface with slag inclusions are shown in Figures 19a and 19b.



a. Fracture Surface.



b. Slag Inclusions.

Figure 19—Fracture Surface of a Plate Bending Fatigue Specimen Containing Surface Slag Inclusions and Surface Appearance of an Unbroken Specimen.

TABLE 4

Fatigue Results for R.R. Moore Tests

Heat No.	1	3
Heat Treatment	N & T	Q & T
Tensile Strength	87,300	121,200
Endurance Limit		
Unnotched	34,500	47,000
Notched	22,000	31,500
Endurance Ratio*		
Unnotched	0.395	0.390
Notched	0.252	0.255
K_t**	2.2	2.2
K_f+	1.57	1.49
q++	0.475	0.408

$$* \text{ Endurance Ratio } = \frac{\text{Endurance Limit}}{\text{Tensile Strength}}$$

** Theoretical Stress Concentration Factor (K_t)

+ Fatigue Strength Reduction Factor

$$(K_f) = \frac{\text{Endurance Limit of Unnotched Specimen}}{\text{Endurance Limit of Notched Specimen}}$$

$$++ \text{ Notched Sensitivity Factor } (q) = \frac{K_f\text{-}1}{K_t\text{-}1}$$

Fatigue Test Results

R. R. Moore Fatigue Specimens.. . The fatigue test results for the Ni-Cr-Mo cast steel (8630) for the R. R. Moore specimens are summarized in Table 4. The endurance ratios for these specimens (QT 0.390 and NT 0.395) showed higher values than the plate bending fatigue specimens (QT 0.282 and NT 0.361) from Tables 4 and 5. These results are to be expected since the size and shape of the two specimens were different. It has already been pointed out(9-12) that the smaller the size, the higher the endurance ratio: and Raghaven(35) has shown that for equal bending moment, the strain is greater in the rectangular bending specimens than in the round R. R. Moore specimens. It has been shown(36) that testing speed, at room temperature in non-corrosive atmosphere, has little or no effect up to 10,000 cycles per minute, so little influence would be anticipated from this variation.

Bending Fatigue Specimens . . . Table 5 lists the heat treatments, tensile strengths, discontinu-

TABLE 5

Summary of Fatigue Results for Bending Fatigue Specimens

Heat No.	Heat Treatment	Tensile Strength (psi)	Discontinuity	Endurance Limit (psi)	Endurance Ratio*
6	Q T	145,000	Cast Steel - Sound	45,000	0.310
8	Q T	128,000	Hot Tear	35,000	0.274
6	Q T	137,000	Quench-Cracks	36,200	0.264
4	Q T	122,000	Weld-Machine-Sound	30,600	0.251
9	Q T	122,000	Slag Inclusions	30,000	0.246
4	Q T	122,000	Weld-Slag	29,700	0.243
4	Q T	122,000	As Welded-Sound	29,450	0.241
3	Q T	121,200	Weld-Incomplete Penetration	29,100	0.240
3	Q T	121,200	Weld-Undercut	28,300	0.233
2	Q T	126,000	Cavities	14,700	0.117
7	N T	83,100	Cast Steel - Sound	30,000	0.361
4	N T	89,800	Weld-Machine-Sound	31,500	0.352
3	N T	88,300	Weld-Incomplete Penetration	31,100	0.350
4	N T	89,800	As Welded-Sound	30,900	0.345
4	N T	89,800	Weld-Slag	28,200	0.314
9	N T	88,900	Slag Inclusions	26,000	0.292
3	N T	88,300	Weld-Undercut	24,800	0.280
4	N T	89,800	Hot Tear	22,000	0.245
2	N T	82,300	Cavities	19,300	0.235

Q T = Quenched and Tempered
N T = Normalized and Tempered

$$* \frac{\text{Endurance Limit}}{\text{Tensile Strength}} = \text{Endurance Ratio}$$

ities, endurance limits and endurance ratios for the bending fatigue specimens. The endurance ratios have been arranged such that they are decreasing from top to bottom which aids in vizualizing the effect of the discontinuity on the fatigue properties.

The data were plotted as conventional S-N diagrams comparing cast steel without discontinuities to that containing the various types of discontinuities. The data obtained by fatigue testing were processed on the basis that the load imposed on one group of specimens (sound, quench-cracked, welded and machined, weld slag inclusions and welded-sound specimens) was converted to maximum stress at the outer fibers by using elementary mechanics that are based on the gross cross section of the specimen. The other group of specimens (weld-incomplete penetration, weld-undercut, cavities, hot tears, and surface slag inclusions) were so defective that the scatter due to the loss of cross-sectional area from the discontinuities was large. In order to reduce this problem, the stress was calculated by taking into account the loss in cross-sectional area resulting from the discontinuities. Curves (S-N) for all torsion and plate bending specimens were drawn through the lower data points in order to provide more conservative design values of fatigue strength.

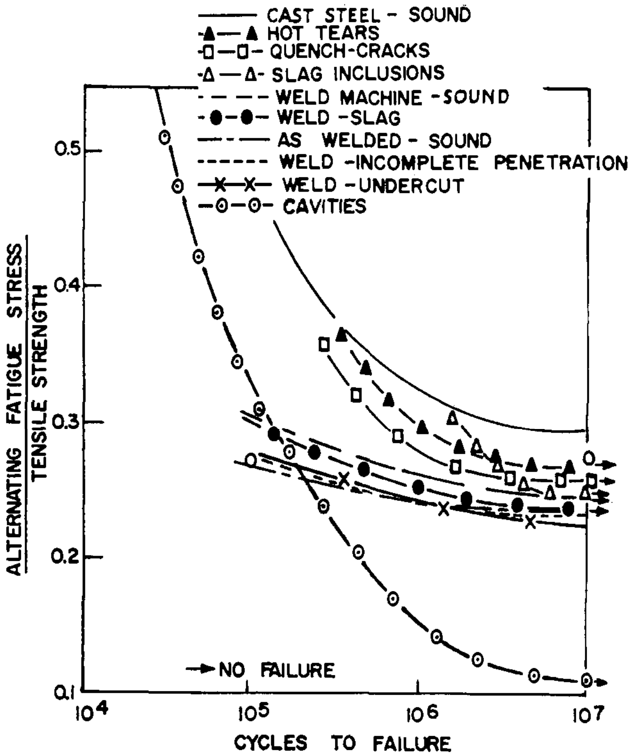


Figure 20—Relation Between $\frac{\textit{Alternating Fatigue Stress}}{\textit{Tensile Strength}}$ *and Number of Cycles to Failure for Bending Fatigue Specimens Quenched and Tempered Condition.*

Comparisons of fatigue strength resulting from various discontinuities can be misleading if only the absolute values of stress, for example, endurance limit, are employed. It is more meaningful to use the ratio of testing stress to tensile strength plotted versus cycles to failure for comparative S-N curves. Such a representation eliminates the influence of varying tensile strengths between the different heats and heat treatments.

The S-N curves drawn in this manner for the bending specimens appear in Figures 20 and 21. The fatigue strength of the specimens containing the severe discontinuities was less than that of the sound cast steel.

The degree of scatter in both the normalized and tempered and quenched and tempered cavity specimens was considerable. This scatter occurs because of the approximation made when calculating the area of the load-supporting material. This area was then used in calculating the corrected stress values.

The flatness of the S-N curves for welded specimens compared to the sound cast steel is apparent in Figures 20 and 21. The notch sensitivity of the cavity and quench-cracked specimens decreases at higher stress or lower life. This occurs because the discontinuities are randomly dispersed and only constitute a small volume in the test section of the sound material. At the high stresses, the material can yield in the vicinity of this small number of discontinuities and reduce the notch sensitivity.

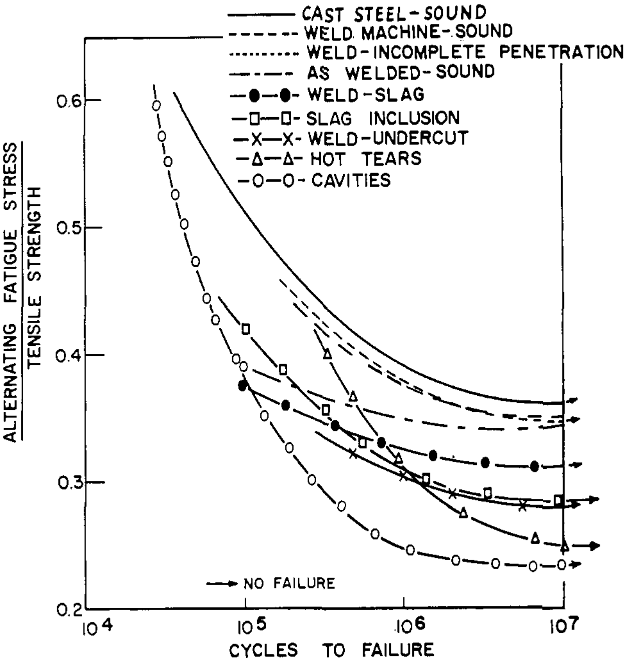


Figure 21—Relation Between $\frac{\textit{Alternating Fatigue Stress}}{\textit{Tensile Strength}}$ *and Number of Cycles to Failure for Bending Fatigue Specimens Normalized and Tempered Condition.*

The following comments are offered as an explanation for the stress sensitivity of the welded specimens. This explanation also applies to the sound welded specimens tested in this investigation. A hardness traverse across the cast steel and weld deposit section of the welded fatigue specimen after heat treatment is shown in Figures 22 and 23. Both illustrations show that the hardness level, and consequently the strength level, of the deposited weld after heat treatment is lower than the cast steel. It is estimated, based on the hardness, that the tensile strength is 3000 to 4000 psi lower in the weld deposit. A corresponding lower yield strength would be anticipated. This lower strength level of the weld deposit acts as a discontinuity in the material, over relatively large area, since the weld is deposited over the cross-sectional area.

Other investigators(37, 38) show that the lower strength portion of the specimen is the governing factor in determining the fatigue strength of the specimen. The larger, weaker area provides the greater stress and/or based on the discontinuity in strength, a higher fatigue notch sensitivity.

Considerable significance can be attached to the above considerations because of the importance of limited fatigue life for some applications, where parts are subjected only to several thousand or several hundred thousands of cycles. In such cases, the reporting of the notch sensitivity at infinite life (10^7 cycles for steel) may neglect significant information at the lower cycle region. The fatigue strength reduction factor, K_f, indicates the effect of severe discontinuities on the fatigue strength at the different endurance life and Table 6 lists these values for bending fatigue. All the welded specimens show an increase in sensitivity as the applied load increases, whereas, K_f decreases in the unwelded steel. An alternate way of indicating the notch sensitivity in fatigue is by the use of an equation defining the S-N curve in the limited endurance region. It has been found(39) from many fatigue tests of small machined and polished rotating beam specimens of steel, that the portion of the S-N curve between N equals about 50,000 to N equals 4,000,000 can be represented by the empirical equation,

$$S = \frac{k_1}{Nk_2} \qquad (2)$$

in which k_1 and k_2 are constants and S and N are the maximum stress and number of cycles to failure, respectively. This equation can be applied even though discontinuities are present. Table 6 lists the values of k_1 and k_2. Values for k_2 of 0.13 to 0.15 for sound steel at the strength levels of this study have been quoted by many sources(39). Note the low values of k_2 for the welded material, indicating a high notch sensitivity. The sound cast steel falls within the usual range (0.13 0.15).

Finally, the fatigue strength of the welded and machined specimens lies below the sound cast steel; this indicates the effect of the weld in reducing the fatigue strength. In some cases, the weld has been reported to have the same fatigue strength as the cast steel(40). However, the reason for the observed reduction found in this study is the lower hardness of the weld metal compared to the cast steel as indicated by Figures 22 and 23. The reason for the decrease is the difference in alloy content and hardenability(38) in the weld zone, since commercial welding electrodes of slightly different composition than the base metal were employed. The endurance limit of the welded fatigue specimens containing slag inclusions, undercut, incomplete penetration discontinuities, and sound weld specimens lie below the endurance limit of the welded and machined specimens. This

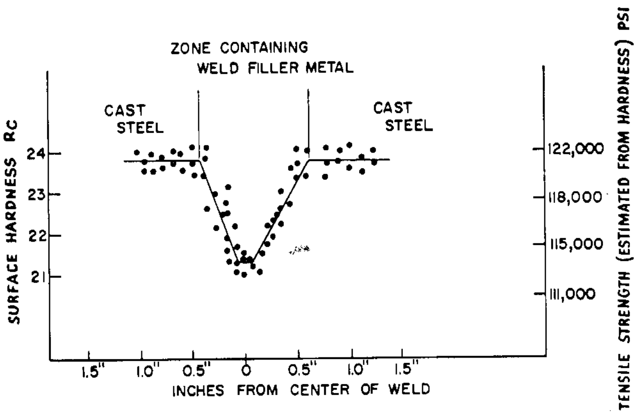


Figure 22—Hardness Profile for Welded Fatigue Specimens After Quenching and Tempering.

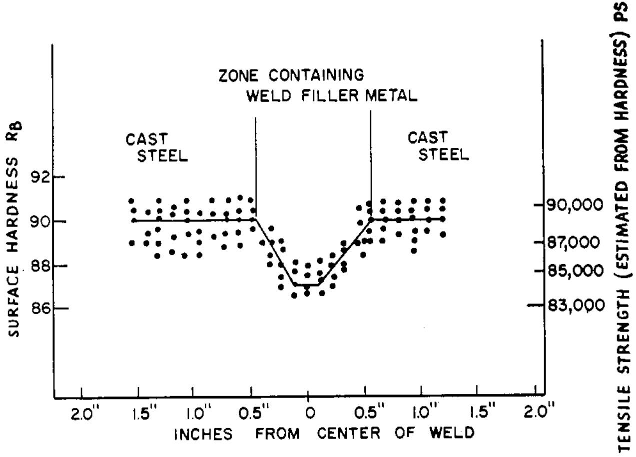


Figure 23—Hardness Profile for Welded Fatigue Specimens After Normalizing and Tempering.

illustrates the additional effect these discontinuities have in reducing the fatigue strength when located in the weld zone. Thus, it is advisable to remove slag inclusions, incomplete penetration, and undercut discontinuities from the weld zone.

Torsion Fatigue Specimens . . . The fatigue results for reversed torsion studies are summarized in Table 7.

The shear stress was calculated using total cross-sectional area except for the weld undercut specimens where the minimum area in the undercut was used. The severity of the hot tears varied so that it was necessary to take into consideration the decrease in load supporting area. This was done by assuming circular arc-grooves in a round shaft. The shear stress in the torsion bars containing gas cavity discontinuities could not be calculated, since no theory to date has been developed to present a computation of the effect of holes of varying shape, size and location or shear stress. In place of the shear stress, the applied load used to cause failure was employed and was divided by the load corresponding to the tensile strength of the material to obtain the endurance ratio. Figures 24 and 25 show the data plotted as endurance ratio versus number of cycles to failure; this method of plotting eliminates the problem of small variations which occurred in the tensile strength of the torsion specimen. The variation in endurance ratio is seen to be larger for cast steel in the quenched and tempered than the normalized and tempered heat treated condition. The notch sensitivity of the quenched and tempered specimens is greater than that for the normalized and tempered material. The increased notch sensitivity in the quenched and tempered material is the result of the higher tensile strength. The shape of the S-N curves in the limit fatigue range for the torsion specimens do not vary to the extent as does the same region in the bending fatigue S-N curves. The same conclusion can be obtained if the k_2 values of equation 2 for bending and torsion are compared. These are listed in Table 8. The variation in the k_2 values are seen to be less in torsion than in bending fatigue. The small spread in K_f values listed in Table 9, for various values of endurance life, also indicates the lower notch sensitivity at equivalent strength levels in torsion than in bending.

Comparison of Fatigue Strengths in Bending and Torsion . . . The theory of elasticity shows that for an isotropic material, a constant relationship or ratio should exist between the torsion stress and the tension stress required to cause fatigue failures. The predicted values of this

TABLE 6

K_f Values for Severe Discontinuities in Bending Fatigue at Various Values of Endurance Life

Type of Specimen	Endurance Ratio	Endurance of Life (K_f) 10^5	10^6	10^7	$k_1 x 10^5$	k_2
Q T						
Cast Steel-Sound	0.310				3.31	0.14
Hot Tears	0.274		1.08	1.13	20.10	0.15
Weld-Machine	0.251	1.33	1.14	1.13	0.82	0.07
Slag Inclusions	0.246		0.96	1.26	18.6	0.24
As Welded-Sound	0.241	1.52	1.23	1.17	0.50	0.04
Weld Incomplete Penetration	0.240	1.49	1.23	1.18	0.63	0.05
Weld-Slag	0.243	1.35	1.19	1.16	0.76	0.06
Quench-Cracks	0.264		1.06	1.07	4.20	0.17
Weld-Undercut	0.233	1.46	1.23	1.21	0.64	0.05
Cavities	0.117	1.28	1.96	2.41	22.00	0.34
N T						
Cast Steel-Sound	0.361				1.90	0.13
Weld-Machine	0.352		1.04	1.03	1.30	0.10
Weld-Incomplete Penetration	0.350	1.23	1.03	1.03	0.59	0.04
As Welded-Sound	0.345	1.32	1.12	1.05	0.56	0.04
Weld-Slag	0.314	1.38	1.20	1.15	0.68	0.06
Slag Inclusions	0.292	1.11	1.22	1.24	8.63	0.12
Weld-Undercut	0.280		1.29	1.29	1.10	0.10
Hot Tears	0.245		1.22	1.48	1.62	0.45
Cavities	0.235	1.34	1.59	1.54	7.70	0.27

TABLE 7

Summary of Fatigue Results for Torsion Fatigue Specimens

Heat No.	Heat Treatment	Tensile Strength (psi)	Discontinuity	Endurance Limit (psi)	Endurance Ratio*
2	Q T	126,000	Cast Steel-Sound	37,600	0.298
9	Q T	122,000	Slag Inclusion	30,000	0.246
5	Q T	124,100	Weld-Machine	28,500	0.230
5	Q T	124,100	As Welded-Sound	27,400	0.221
3	Q T	121,200	Weld-Undercut	23,600	0.195
5	Q T	124,100	Weld-Slag Inclusions	22,700	0.184
1	Q T	132,000	Hot Tears	19,300	0.146
2	Q T	126,000	Cavities	120 lb+	0.100+
7	N T	83,100	Cast Steel-Sound	23,600	0.270
5	N T	90,200	Weld-Machine	23,600	0.261
5	N T	90,200	As Welded-Sound	22,600	0.250
1	N T	87,300	Hot Tears	21,100	0.241
5	N T	90,200	Weld-Slag	21,200	0.234
3	N T	88,300	Weld-Undercut	20,300	0.230
9	N T	88,900	Slag Inclusions	18,500	0.208
2	N T	82,300	Cavities	140 lb+	0.195+

* $\frac{\text{Endurance Limit}}{\text{Tensile Strength}} = \text{Endurance Ratio}$

+ $\frac{\text{Minimum Load (lb)}}{\text{Load at T.S. (lb)}}$

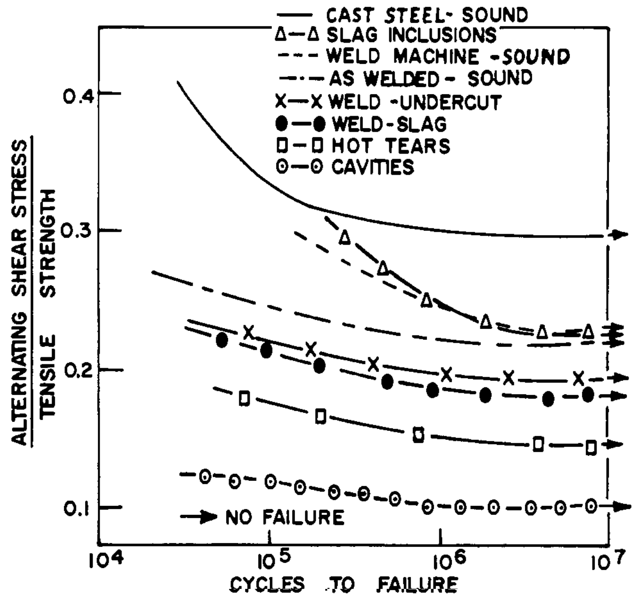


Figure 24—Relation Between $\frac{\textit{Alternating Shear Stress}}{\textit{Tensile Strength}}$ *and Number of Cycles to Failure for Torsion Fatigue Specimens Quenched and Tempered Condition.*

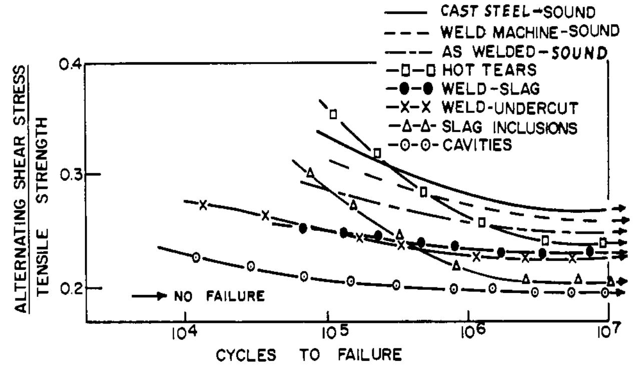


Figure 25—Relation Between $\frac{\textit{Alternating Shear Stress}}{\textit{Tensile Strength}}$ *and Number of Cycles to Failure for Torsion Fatigue Specimens Normalized and Tempered Condition.*

TABLE 8
Empirical Constant for Torsion Fatigue Specimens

Type of Specimen	Heat Treatment	Endurance Ratio	$k_1 \times 10^5$	k_2
Cast Steel-Sound	Q T	0.298	1.30	0.09
Slag Inclusions	Q T	0.230	1.32	0.09
Weld-Machine-Sound	Q T	0.230	1.30	0.10
As Welded-Sound	Q T	0.221	0.58	0.06
Weld-Undercut	Q T	0.195	0.47	0.05
Weld-Slag	Q T	0.184	0.44	0.05
Hot Tears	Q T	0.146	0.62	0.08
Cast Steel-Sound	N T	0.270	0.62	0.07
Weld-Machine-Sound	N T	0.261	0.58	0.05
As Welded-Sound	N T	0.250	0.43	0.04
Hot Tears	N T	0.241	1.40	0.13
Weld-Slag	N T	0.234	0.03	0.02
Weld-Undercut	N T	0.230	0.09	0.04
Slag Inclusions	N T	0.208	1.42	0.04

ratio of torsion fatigue strength (t) to bending fatigue strength (b) for each of the yielding criteria usually employed in fatigue are listed below. Predicted ratio of:

$$\frac{\text{Fatigue Strength in Torsion (t)}}{\text{Fatigue Strength in Bending (b)}}$$

Maximum shear stress = 0.5

Maxwell-VonMises strain energy criterion = 0.577

Figure 26 compared the endurance ratios in bending and torsion for the quenched and tempered and normalized and tempered cast Ni-Cr-Mo (8630) steel with and without various kinds of discontinuities. Lines representing the two yielding criteria are plotted for comparison with the experimental results.

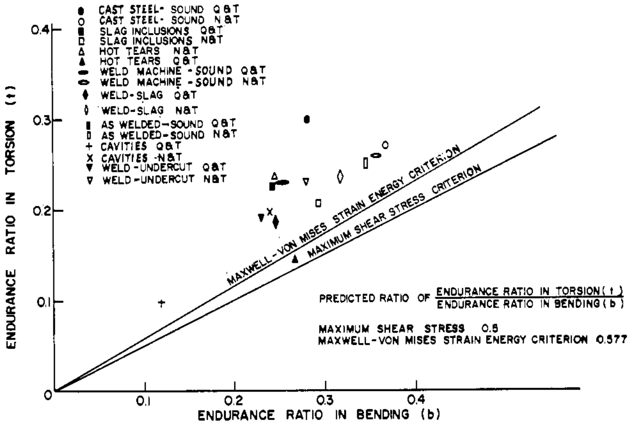


Figure 26—Illustrates Endurance Ratio in Torsion Versus Endurance Ratio in Bending for Cast Ni-Cr-Mo 8630 Steel.

TABLE 9
K_f Values for Torsion Fatigue Specimens at Various Values of Endurance Life

Type of Specimen	Endurance Life 10^5	10^6	10^7
Q T			
Slag Inclusions		1.32	1.37
Weld-Machine-Sound		1.22	1.30
Slag Inclusions			1.30
As Welded-Sound	1.37	1.35	1.35
Weld-Undercut	1.50	1.51	1.53
Weld-Slag	1.55	1.61	1.62
Hot Tears	1.88	1.96	2.05
Cavities	2.83	2.94	2.98
N T			
Weld-Machine-Sound	1.06	1.03	1.03
Hot Tears	.93	1.07	1.12
As Welded-Sound	1.17	1.09	1.08
Weld-Slag	1.34	1.21	1.15
Weld-Undercut	1.34	1.23	1.17
Slag Inclusions	1.11	1.25	1.21
Cavities	1.61	1.42	1.39

The ratio of torsion to bending (t/b) varies widely for the various kinds of discontinuities tested, Accordingly, no one criterion is adequate to describe the general behavior. However, the ratio of fatigue strength in torsion and bending lie between 0.53 and 1.06. The sound cast steel has better properties both in bending and torsion, than the cast steel containing discontinuities. Two conclusions can be drawn from the plotted results of Figure 26. First, all the points except one lie above the Maxwell-VonMisses criterion indicating that discontinuities present in torsion are not nearly so damaging as they are in bending. This can be concluded since the equivalent endurance ratios in torsion compared to those in bending would be lower by 0.577, when calculated by the Maxwell-VonMises criterion. If this is done, then the actual endurance ratios in torsion are found to be higher than those in bending. Second, the endurance ratio in bending and torsion is higher for the normalized and tempered cast steel than the quenched and tempered cast steel.

It is of interest to compare cast metals with wrought metals with and without discontinuities present. Ludwik(41) and many others (41-46) have shown that wrought material free of discontinuities has an average t/b ratio between 0.54 to 0.60. The lower values are obtained with magnesium alloys and the higher for steel. These materials appear to follow the Maxwell-VonMises strain energy criterion. For cast metals, the average (t/b) ratio varies from 0.70 to 1.05. The lower ratios are for cast magnesium and higher results for iron. The value of t/b is considerably higher for unnotched cast metals than for unnotched wrought metals. On the other hand, both cast and wrought metals containing discontinuities show the same average (t/b) ratio (from 0.70 to 1.1). Thus, it can be concluded that wrought metals are more notch sensitive than cast metals.

Table 10 lists the endurance ratios for both bending and torsion along with the t/b ratios. The t/b ratio for the quenched and tempered hot tear discontinuities is below the average t/b ratio because of the approximations used in calculating the stress. These approximations have a greater effect on the quenched and tempered materials since it is more notch sensitive than in the normalized and tempered condition.

Goodman Diagram.. . The fatigue strength of specimens containing discontinuities depends on the type of load application, since stresses which produce failure under repeated fluctuating loads may be harmless when the load is static. The maximum stress which this material can sustain depends upon the relationship between steady stress and alternating stress. A well-known method of depicting this relationship is the Goodman diagram.

Figures 27, 28, 29 and 30 are the Goodman diagrams modified for the variation in the tensile strength of the test specimens on the basis of bending fatigue and torsion fatigue. These figures illustrate the effect of mean stress and the presence of discontinuities on the fatigue behavior of the quenched and tempered and normalized and tempered cast steel. A mean stress had no effect on sound material in torsion up to yielding, thus the absence of stress lines for the sound cast steel specimens in the Goodman diagram. The endurance ratios of all the fatigue specimens containing discontinuities lie below the sound specimen endurance ratio, shown on the ordinate of the Goodman diagram for comparison. This diagram shows how the fatigue strength decreases for various mean loads and illustrates that severe discontinuities lower the fatigue strength of cast steel.

Discontinuities vs. Notched Specimens

A comparison of the effect of pronounced notches can be made by considering the data of Table 10. It will be observed that for sound cast

TABLE 10

Comparison of Endurance Ratios in Bending and Torsion

Type of Specimen	Endurance Ratio In Bending	Endurance Ratio In Torsion	(t/b)**
Q T			
Cast Steel-Sound*	0.310	0.298	0.96
Weld-Machine-Sound	0.251	0.230	0.92
Slag Inclusions	0.246	0.246	1.00
As Welded-Sound	0.241	0.221	0.92
Weld-Slag	0.243	0.184	0.75
Weld-Undercut	0.233	0.195	0.84
Cavities	0.117	0.100	0.86
Hot Tears	0.274	0.146	0.53
N T			
Cast Steel-Sound*	0.361	0.270	0.75
Weld-Machine-Sound	0.352	0.261	0.74
As Welded-Sound	0.345	0.250	0.73
Weld-Slag	0.314	0.234	0.75
Weld-Undercut	0.280	0.230	0.82
Cavities	0.235	0.195	0.83
Slag Inclusions	0.292	0.208	0.71
Hot Tears	0.245	0.241	0.98

** $(t/b) = \frac{\text{Endurance Ratio in Torsion}}{\text{Endurance Ratio in Bending}}$

* Endurance Ratio using R.R. Moore Specimen
Q T unnotched .390
Q T notched .255
N T unnotched .395
N T notched .252

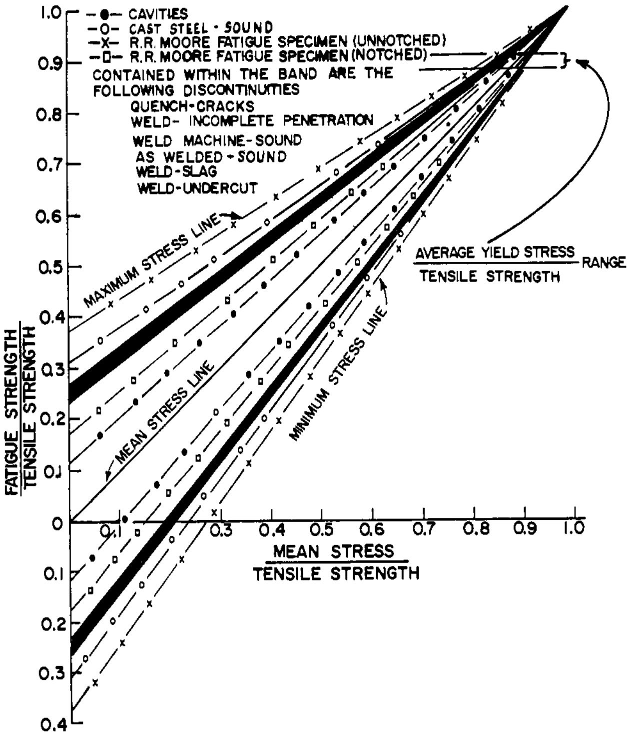


Figure 27—Goodman Diagram for Bending Fatigue Specimens Quenched and Tempered Condition.

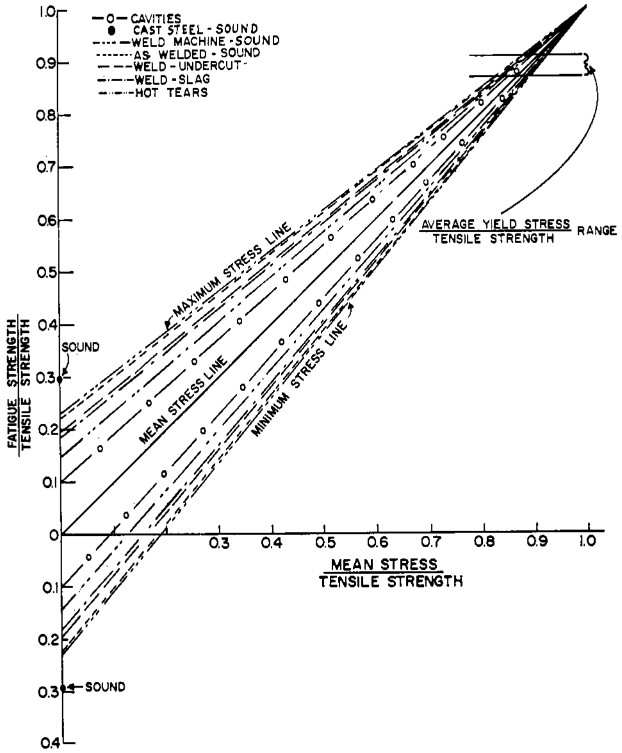


Figure 28—Goodman Diagram for Torsion Fatigue Specimens Quenched and Tempered Condition.

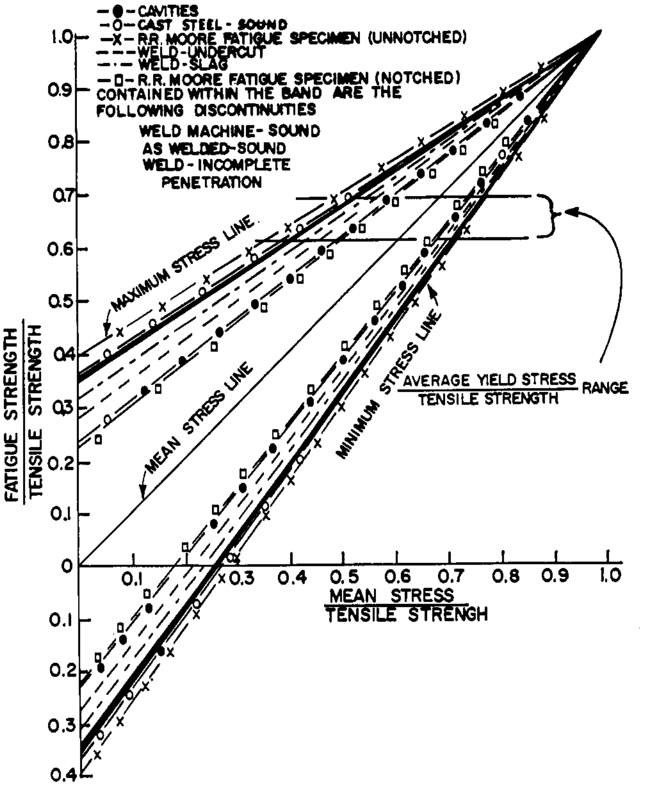


Figure 29—Goodman Diagram for Bending Fatigue Specimens Normalized and Tempered Condition.

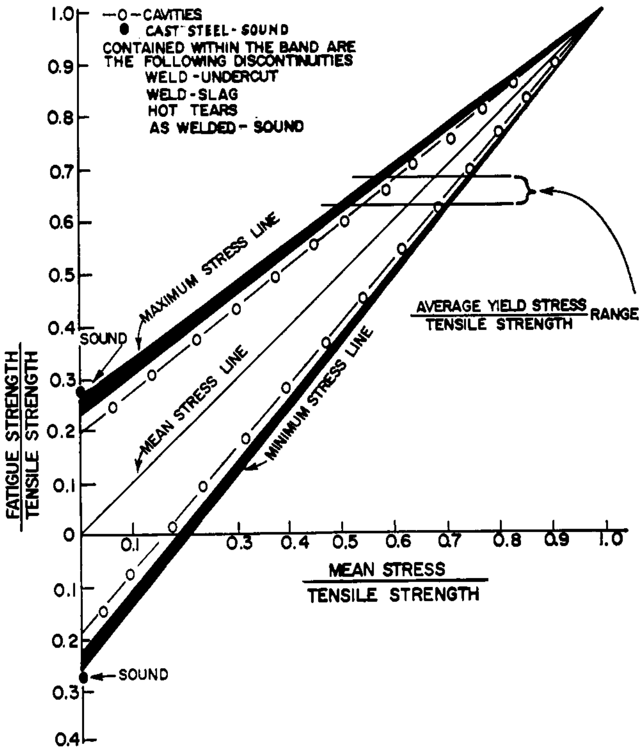


Figure 30—Goodman Diagram for Torsion Fatigue Specimens Normalized and Tempered.

steel sections the endurance ratio changes depending on the type of specimen. The R. R. Moore unnotched specimens provide the highest endurance ratio values and design criteria based on endurance strength usually employ unnotched values based on fatigue testing with R. R. Moore specimens. A safety factor of 3 is usually employed because of dynamic stresses of torsion, bending, and notch effect. If the notched endurance strength is employed, a safety factor of 1.5 is used.

In order to compare the endurance ratio in torsion to that in bending, the Maxwell-VonMises strain energy criterion has to be employed. The endurance ratio in torsion (shear) is divided by 0.577 to obtain the equivalent ratio as that in bending. Resulting endurance ratio in torsion for the specimens containing the various discontinuities lies between 0.252 and 0.418. The above range of endurance ratios for both bending and torsion specimens applies to all the types of discontinuities except the very severe gas cavities. The endurance ratios in bending and torsion are of greater or equal magnitude compared to that of the notched R. R. Moore specimens which was 0.25. These discontinuities then provide less or equal damage to fatigue behavior as a severe notch.

It must be remembered that the discontinuities studied were for the most part located on the specimen surface. These are most detrimental to fatigue because of the concentration of stress and location of fatigue failure at the surface. Furthermore, the discontinuities were extremely severe for the sections being tested and according to non-destructive testing reference standards would not comply with any class for commercial steel castings. Since the discontinuities investigated in this study were more severe than those contained in non-destructive inspection standards (ASTM E71, E99 and E125), it is anticipated that the discontinuities described in these standards would exert a somewhat less damaging effect on fatigue behaviors.

CONCLUSIONS TO RESEARCH REPORT

The following conclusions can be drawn from the results of this investigation.

1. The fatigue strength in bending and torsion of small scale specimens was lowered by the presence of severe surface discontinuities as compared to that of sound cast steel specimens.

2. All the discontinuities present in the cast steel were found to be more damaging in reverse bending than in reverse torsion.

3. Bending fatigue specimens were more notch sensitive with decreasing endurance life than the corresponding endurance life for torsion.

4. The cast steels were less notch sensitive in the normalized and tempered than in the quenched and tempered condition.

5. The cast steel specimens which were welded and machined had a lower endurance limit than the sound cast steel specimens. Those cast steel welded specimens which contained slag inclusions, incomplete penetration, and undercut weld discontinuities had a lower endurance limit than the welded cast steel. These results indicate that discontinuities present in the weld zone are harmful.

6. Only severe surface discontinuities were evaluated in these studies. These discontinuities were of greater severity than permitted by ASTM E71, E99 or E125.

7. The presence of the severe surface discontinuities in the cast steel lowered the endurance strength and ratio to the same or less extent as the presence of notches in the standard (R. R. Moore) fatigue tests.

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