LOW-CYCLE FATIGUE OF MATERIALS FOR SUBMARINE CONSTRUCTION

RESEARCH AND DEVELOPMENT REPORT 91 197D
SUB-PROJECT S-R007 01 01
TASK 0856

14 FEBRUARY 1963

BY

M. R. GROSS

**United States Naval
Engineering Experiment Station
Annapolis, Maryland**

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ANNAPOLIS, MARYLAND

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Abstract

Materials for submarine construction were investigated to determine their low-cycle flexural fatigue behavior. Both ferrous and nonferrous materials, including five steels with yield strengths of 40,000 to 230,000 psi, five nickel-base, six aluminum-base and three copper-base alloys were used in the study. Comparisons on the basis of three parameters: plastic-strain range, total-strain range, and nominal reversed stress, were made of the effects of mechanical notches, cycle pattern, weldments, and salt-water corrosion. It is concluded that the relationship between total-strain range and life is similar for all the materials investigated and that it offers a more general and practical approach to design than plastic-strain range or nominal reversed stress.

I. Introduction

The majority of engineering problems involving the fatigue of metals are directly concerned with adequate life under many millions of stress cycles. The approach to such problems is essentially to design for infinite life, and over the years designers have developed adequate design procedures based on elastic theory and empirical data. As one might expect, the infinite-life approach extracts a penalty, especially in weight, when only short or finite fatigue life is required.

In the last two decades, a great many developments in science and engineering have called for a relaxation of the infinite life concept, especially where weight is critical, as in missiles, high-pressure vessels, pipework, and certain aircraft components. These demands, coupled with advances in the knowledge of plastic theory and a better understanding of elasto-plastic states, have encouraged designers to consider a finite life approach to certain engineering problems.

In order to understand, utilize, and control the vast reaches of the oceans, future research vessels and combat submarines will be expected to descend and operate at increasingly greater ocean depths. Such accomplishment will require the utilization of materials of higher strength-to-weight ratio, particularly high-strength steels, titanium alloys, and reinforced plastics. Furthermore, present design concepts will undoubtedly need modification and innovation.

In considering this situation, several years ago, Bureau of Ships designers reasoned that pressure cycles induced by maneuvering deep diving submarines to various depths might possibly limit the life of the pressure hull and certain internal equipments of the submarine. The basis for this reasoning was that structures exposed to sea water pressure and corrosion would be subjected to a finite number of high stress cycles and therefore the structures' useful life might well be dictated by the resistance of materials to so-called low-cycle fatigue. Accordingly, certain experimental investigations were authorized and conducted. It is the purpose of this paper to present and discuss the results obtained in an investigation of the low-cycle fatigue behavior of metallic materials for submarine construction.

II. Low-Cycle Fatigue Defined

There is general agreement that low-cycle fatigue as applied to metallic materials is concerned with lifetimes of less than one million cycles. The word "low" refers to the number of cycles to failure, and not to the severity or intensity of the stresses. The fact is that the nominal stresses necessary to produce failures in several thousand cycles are usually above the initial yield strength of the metal. Thus, low-cycle fatigue normally involves plastic deformation of the metal and is sometimes called "plastic strain fatigue."

III. History and Literature

Low cycle fatigue has been under serious study since about 1942. Actually, Kommers [1] reported the results of some low-cycle fatigue tests in 1912, but, as so often happens, the need was not present and the subject lay dormant for some 30 years.

It is not the purpose of this paper to present a detailed review and analysis of the published literature, inasmuch as this has already been done in two recent papers. Benham [2] presents an excellent summary and analysis of some 50 references dating to 1957. Yao and

Munse[3] likewise review and analyze the subject through 1961. Certain basic concepts, however, that contribute to the results or discussion are reviewed below.

There is general agreement that low-cycle fatigue is a function of strain and that the following relationship, or some modification thereof, describes the behavior of metallic materials in the low-cycle range.

$$\epsilon N^m = c \tag{1}$$

ϵ = true strain range

N = cycles to failure

m and c = material constants

Complete agreement is lacking, however, whether ϵ should be the plastic strain range, ϵ_p, or the total strain range (elastic + plastic), ϵ_T. Also, the question sometimes arises whether ϵ should be the true strain as indicated or the engineering strain, e. The strains are related as follows:

$$\epsilon = \ln(1 + e) \tag{2}$$

A few calculations will show that the question is for the most part academic for strains below 5%.

Tavernelli and Coffin[4] compared equation (1) with data on a variety of materials. They concluded that the following form of the generalized equation could be used to establish the strain-life relationship of a material from the results of a simple tension test.

$$\epsilon_p N^{1/2} = \frac{\epsilon_f}{2} = \frac{1}{2} \ln \left(\frac{100}{100 - \%RA} \right) \tag{3}$$

where ϵ_p = plastic strain range, in./in.

N = cycles to failure

ϵ_f = true fracture strain (fracture ducility) in./in.

RA = reduction in area

Basically, the investigation described herein extends the work of Gross, Stout, et al.[5, 6, 7] to materials for submarine construction. Professor Stout and his coworkers at Lehigh University have conducted an extensive series of low-cycle fatigue tests under the auspices of the ASME Pressure Vessel Research Committee. Inasmuch as the hull of a submarine is a pressure vessel problem, it was logical to continue on the basis of work under way at Lehigh.

IV. Description of Material

The materials investigated, together with their approximate chemical composition and tensile properties, are listed in Table 1. Not all of these materials are under serious consideration as structural materials for submarine hulls and associated equipment exposed to sea pressure. However, the general lack of low-cycle fatigue information dictates its publication when available. The main interest lies in the use of steel for the pressure hulls and of nickel and copper-base alloys for salt water piping, fittings, water boxes, etc. Currently, data are being developed on titanium and its alloys.

Figure 1 shows typical true stress-true strain diagrams for HT and HY-100 steels. These illustrate the decrease in yielding plateau observed with increasing strength. Included in Table 1 is sufficient information to contruct close approximations of the true stress-true strain curves for all of the materials. The method of construction is shown in Figure 2.

V. Method of Test

All of the low-cycle fatigue tests described herein are of the completely reversed constant deflection flexural type. The smooth and notched specimens, Figure 3, are identical to those used by Gross and Stout [5, 6, 7] in their study of pressure vessel steels. The welded specimen, Figure 4, differs from that of Gross and Stout.

The machines shown in Figure 5 were designed and constructed specifically to study the behavior of materials when subjected to cyclic plastic strains. Figure 6 is a schematic drawing of one machine. The short end of the specimen is rigidly fixed to the base of the machine, and a bending moment is applied through a weigh bar to the free end by a double-acting hydraulic cylinder. The direction of the cylinder is controlled by a four-way solenoid valve. Reversing of the cylinder is accomplished either by electrical contact of the specimen with deflection control micrometers as shown in Figure 6, or by an electrical timer and mechanical stops. With the former method, a saw-tooth strain-time pattern, Figure 7a, is formed whereas with the latter method a square-wave pattern, Figure 7b, is formed. All of the tests using the micrometer stops were run at 1 cpm. The timed cycles varied between 5 cpm and 0.02 cpm.

The cyclic strains developed in the test section of the fatigue specimens were measured with resistance-type strain gages. Although both wire- and foil-type gages were used, the majority of tests were conducted with etched foil gages similar to BLH-FAP-25-12. This is a paper-backed 120-ohm gage having a 1/4 in. gage length. The gages were applied longitudinally at the various locations shown in Figures 3 and 4. The transverse center line of the gage was placed at the minimum cross section. Prior to offsetting the gage of the welded specimens as shown in Figure 4b, the effect on longitudinal strain was determined. Experiments showed no signifcant difference between the location shown and the normal location at the longitudinal center line.

The bending load applied to the specimens was determined from resistance-type strain gages attached to the weigh bar shown in Figure 6. The dimensions and strength of the weigh bar are such that only elastic strains occur within the load range of the machine. Therefore, the applied load and corresponding moment are a linear function of strain.

The strain-measuring gage on the specimen and the load-measuring gages on the weigh bar are connected into separate Wheatstone bridge circuits. The outputs of these bridges are fed into separate axes of a Moseley Model 2S two-axis recorder. Accordingly, the applied bending load and strain in the test section of the specimen are plotted simultaneously. For specimen strains beyond the proportional limit, a mechanical hysteresis loop similar to that shown in Figure 8 is developed. Various parameters can be obtained from the loop as shown in the figure. Frequent reference will be made to these parameters.

It was observed that under conditions of constant deflection, all of the parameters in Figure 8 undergo changes during the early stages of strain cycling. The magnitude and direction of these changes depend upon whether the material is subject to "cyclic-strain hardening" or "cyclic-strain softening." It was observed that for cyclic plastic strain ranges above about 0.001 in. per in., the shape and size of the loop tended to stabilize within 10 cycles. Similar findings have been reported by Gross and Stout [7] and others. For cyclic plastic strain ranges below 0.001 in. per in., however, complete stabilization did not occur within 100 or more cycles. For the purpose of this phase of the investigation, the loop was considered to be stable at 10 cycles regardless of the plastic strain range.

Elastic stress calculations on the fatigue specimen show that the maximum fiber stress is not developed at the minimum cross section but at approximately 0.028 in. beyond the minimum section towards the fixed end. In general, however, plastic strain fatigue failures on smooth base metal specimens did not occur at a precise location, but tended to fall in about a 1/4-in.-wide band extending across the specimen. Elastic stress calculations show a variation of approximately 4% in the maximum longitudinal fiber stress in this region.

To secure the test when cracks occur in the specimens, a No. 36 Formex insulated copper wire grid is cemented to the test section. The grid constitutes a part of the electrical control circuit. As a crack forms and develops in the specimen, it causes a break in the grid. This interrupts the control circuit and strain cycling ceases. In general, the end point in the test was reached when one or more fatigue cracks became 1/8- to 3/16-in. long.

IV. Results of Tests

The results presented in this paper are based on data obtained from 257 separate, individual tests*. The data have been combined in various ways to study (1) the relationships between life and three parameters, namely, plastic strain range (ϵ_p), total strain range (ϵ_T), and maximum reversed nominal stress (S_R); and (2) how these relationships are influenced by factors such as cycle pattern, notches, salt-water corrosion, etc. Comparisons have been made on the basis of linear log-log lines of best fit derived by standard statistical procedures. Some 114 relationships were studied. In general, the fit of the linear relationships was quite good as evidenced by the fact that

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*Copies of the original data may be obtained from the author.

74% of the relationships had a correlation index (r^2) of 0.90 or higher with 60% exceeding 0.95. A correlation index of 1.0 indicates perfect correlation.

A. Steels

The regression lines obtained for steel are shown in Figure 9. Beneath the graph are the function constants for the three parameters. Included also are the number of tests involved in computing the regression lines.

Several things are apparent in analyzing Figure 9. On the basis of ϵ_P, cycles to failure shows a progressive decrease with increase in strength. The opposite is true for ϵ_T and S_R. Two of the three HY-230 steel specimens exhibited no plastic strain, yet failed in less than 10,000 cycles. The failure of the plastically strained HY-230 specimen was catastrophic; that is, complete fracture occurred after the initiation of a small crack. This is indicative of the high susceptibility of this steel to low energy crack propagation at this strength level.

The variations in slope of the regression lines for ϵ_P are inconsistent with the observations of Travernelli and Coffin [4], who contend that the slopes of the log ϵ_P vs. log N relationships for most metallic materials are similar and that a value of -1/2 can safely be assumed for engineering purposes. Figure 9 indicates that ϵ_P is a highly variable and sensitive parameter, whereas ϵ_T is less variable.

The consistency of ϵ_T is demonstrated in Figure 10 where the individual test results are plotted. The 95% confidence limits for the results are included. Only the HY-230 shows evidence of being different from the general population. As one would expect, the S_R relationships in Figure 9 are inconsistent, being generally affected by the strength levels of the materials.

B. Aluminum Alloys

Figure 11 shows the relationships obtained for aluminum-base alloys. As was the case for steels, the slopes of the ϵ_P relationships generally increase with strength. An exception to this behavior is the 5456-H321 alloy which had a lesser slope than other alloys of comparable strength. The 7079-T6 alloy behaved in a manner similar to that of the HY-230 steel; i.e., low-cycle fatigue failure occurred in the apparent absence of plastic strain, and complete fracture of the plastically strained specimens occurred instantaneously. The behavior of all of the alloys was so consistent with respect to ϵ_T that a single regression line with limits has been plotted in Figure 11. The S_R relationships were similar to those observed for steel.

C. Nickel Alloys

Relationships for the nickel-base alloys are shown in Figure 12. The results are similar to those observed for the previous alloys. Of particular interest is the fact that the slope of the log ϵ_P vs. log N relationship is approximately -1/2 for Inconel and Nionel. Also, none of the plastically strained, high-strength nickel-base alloys exhibited instantaneous fracture.

D. Copper Alloys

Figure 13 shows the relationships obtained for copper-base alloys. In general, the results were more erratic than observed for other materials. Much of this can be attributed to (1) the normal heterogeneity of cast materials and (2) the limited number of specimens tested. Because of the relatively high variability of the ϵ_T relationships for the copper alloys, the individual regression lines are shown.

E. Effects of Cycle Pattern

As mentioned earlier in the paper, both saw-tooth and square-wave types of load patterns were used in various phases of the investigation. Figure 14 compares the results obtained with these two patterns for HY-100 steel in air. Inasmuch as the square-wave results in air did not seem to be affected by cycle times ranging from 0.067 to 5 cpm, the regression lines shown are for the combined data. The greater sensitivity of the ϵ_P parameter as compared to ϵ_T and S_R is apparent.

F. Effect of Notches

Figure 15 shows the effect of mechanical notches on the behavior of HY-100 steel in air. Of particular note is the convergent response with decreasing life for ϵ_P as compared to the parallel response for ϵ_T and S_R. The latter behavior indicates a constant percentage reduction in life due to the presence of notches.

G. Effects of Weldments

Figure 16 compares welded-specimen data with the regression line for unwelded specimens. It is apparent that although all of the failures involved the weld metal, the weld metal *per se* had little or no effect on cycles to failure in air.

H. Effects of Salt-Water Corrosion

The salt water corrosion tests described below were performed with Severn River water continuously wetting the test area of the specimen. This is a brackish estuary water containing 1/3 to 1/6 the salt content of natural sea water depending upon the season and the tide.

1. Steels

Figure 17 shows the general effect of salt-water corrosion on the behavior of HY-100 steel. The similarity between the effect of corrosion and the effect of mechanical notches (Figure 15) is to be expected if the resultant effect of corrosion is in fact the generation of a notch. The intersection of the salt water curve with the air curve for ϵ_P would infer that salt water may improve the life of the material in the very low-cycle region. Although some of the salt water data lie to the right of the air curve in the region of 500 to 1000 cycles to failure, none of the data fell outside the 95% confidence limits for air. It is possible that the observed effect exists because of notch strengthening. On the other hand, the two curves may well blend into each other. The true behavior in this region would appear to be of little importance from an engineering standpoint.

On the basis of ϵ_T, the salt water life appears to be consistently inferior to that in air. Statistical tests of the grouped data show no significant differences between the two means. However, an analysis of the differences between actual life in salt water and expected life in air on a paired data basis show that there is less than 1 chance in 1000 that the effect of the two environments is the same. From a practical standpoint, Figure 17 indicates that the expected life in salt water is about 1/2 of that in air.

Figure 18 shows the corrosion-fatigue results of a recent experiment in which the cycle time was varied at four different levels of total strain range. The data are plotted on the basis of cycles per day versus days to failure. The trend of the data has been developed into lines of constant total strain range. Extrapolation of these lines, as shown, permits an estimate of the expected life for one or more cycles per day. The limiting case would be for zero total strain range and its consequent zero cycles per day. In the absence of general corrosion, the limiting case would be expected to give infinite life.

The differences between the expected life in air and the actual life in salt water for the sixteen points in Figure 18 are shown in Table 2. It is apparent from the row sums that the effect of salt water increases with decreasing strain levels as one would expect. The column sums show no similar significant effect for cycle time.

Table 2

Effect of Corrosion on HY-100 Steel ($N_{air} - N_{salt\ water}$)

Approx. ϵ_T Level in./in.	Cycle Time - cpm				Row Sums
	1.200	0.300	0.075	0.020	
0.015	242	441	393	259	1,335
0.012	829	847	1,447	743	3,866
0.009	3,021	3,079	1,980	3,902	11,982
0.007	3,486	4,290	6,629	5,725	20,130
Column Sums	7,578	8,657	10,449	10,629	37,313

2. Copper Alloys

Figures 19 through 21 compare the results of a few corrosion-fatigue tests with the results of air tests shown previously in Figure 13. Both the air and corrosion data are too few to merit extensive analysis. The graphs do show, however, the general tendency for the corrosion-fatigue data to fall to the left of the mean air curve, but for the most part well within the confidence limits shown.

VII. Discussion

One of the major problems confronting a structural designer is an interpretation of the requirements of a structure in terms of the mechanical properties of a material. The translation from an engineered structure to material data or vice-versa is a complex, expensive, and time consuming process normally requiring years of experience, model testing, analysis, retesting, reanalysis, etc. The design of structures on the basis of low-cycle fatigue is no exception, and one finds more and more references to the subject in material and design literature.

The work of Coffin and his coworkers [4, 8] is frequently cited in the literature. They represent a continuing effort to understand and utilize low cycle fatigue data in design. The earlier relationship, $\epsilon_p N^{1/2} = c$, proposed by Tavernelli and Coffin [4] has been modified by Langer [9] to incorporate stress rather than strain, and to provide a smooth transition to the endurance limit in the high-cycle region. The modified equation is as follows:

$$S = \frac{Ec}{2N^{1/2}} + S_e \qquad (4)$$

where:

S = stress amplitude, psi

E = modulus of elasticity, psi

N = cycles to failure

S_e = endurance limit, psi

$c = 1/2 \ln \left(\frac{100}{100 - \% RA} \right)$

Langer proceeds to take this equation and show how it can be applied to the design of pressure vessels for low-cycle fatigue. Tavernelli and Coffin [8] checked the modified equation against their experimental data and concluded that the agreement for 12 of 15 materials was conservative and good.

Equation (4) can be solved in terms of total strain, ϵ_T, with the following result

$$\epsilon_T = \frac{1}{2N^{1/2}} \ln\left(\frac{100}{100 - \% RA}\right) + \frac{2S_e}{E} \qquad (5)$$

Comparing the curves for various materials obtained from equation (5) with the actual total strain data described herein results in varying degrees of fit ranging from ultra-conservative to unconservative. Furthermore, many of the good fits cannot be supported by a more rigorous analysis of the data. For example, an analysis of equation (5) reveals that the position of the curve is strongly influenced by the reduction in area, R. A., and the exponent of N which is assumed to be 1/2. As mentioned previously, the data do not generally support the use of an exponent of 1/2, so that the agreement in many cases appears to be fortunate but unsupported.

Kooistra and Lemcoe[10] describe the results of an experimental study to determine the low-cycle fatigue characteristics of two full-size pressure vessels. They attempted to correlate the results with laboratory fatigue tests of the type described herein. It was concluded that the correlation in one case was very good, while in the other was poor.

The results described have demonstrated the consistency of the total strain approach as compared to the plastic strain approach to low-cycle fatigue. Figure 22 shows the ϵ_T regression lines for each of the types of materials and the equation and 95% confidence limits for the combined data. It would appear that an exponent of 1/3 for N would be a good approximation for all of the materials. The total strain range approach offers several advantages. In addition to the consistency already mentioned, total strain range is directly measurable with a strain gage, and thus requires no simultaneous recording of load and strain as does plastic strain range.

It is apparent that much remains to be done in the area of low-cycle fatigue. Future work at the U. S. Naval Engineering Experiment Station will be in the following directions: (1) Continue flexural tests of ferrous and nonferrous materials including titanium; (2) conduct axial fatigue tests of identical specimens on a recently installed ±300,000 lb fatigue machine; and (3) conduct pressurized "box" tests to help bridge the gap between laboratory tests and complex structures. In the latter tests, a rectangular box of 1 or 2-inch thick plate welded on all edges will be subjected to internal cyclic pressure. The peak pressure will produce a calculated maximum stress (elastic theory) equal to 80% of the yield strength of the base plate. Except for explosive loading, the conditions of the test will be equal or more severe than those of a submarine structure. Conditions will include unintentional notches and defects, residual stresses, corrosion, temperature, etc. Such a test should determine the adequacy of the yield strength approach and, if such an approach is inadequate, whether the outcome could have been predicted on the basis of present knowledge of fatigue and/or fracture mechanics.

VIII. Summary and Conculsions

The low-cycle flexural fatigue ($R = -1$) behavior of steels, aluminum alloys, nickel alloys, and copper alloys have been investigated. The materials were compared on the basis of three parameters, namely, plastic strain range (ϵ_P), total strain range (ϵ_T), and nominal reversed stress (S_R). The parameter versus life (N) relationships were studied to determine the influence of various factors such as mechanical notches, cycle pattern, weldments, and salt-water corrosion. The conclusions reached from this investigation are as follows.

1. The observed effects in the low-cycle region depend to a large extent on the parameter being considered. Plastic range is the most variable and most sensitive parameter. Total strain range is the least variable, and nominal reversed stress is the least sensitive.

2. Slopes of the log ϵ_P versus log N relationships range from -0.42 to -2.40 and generally decrease with increasing strength for a given type of material. The assumption that the slope is a constant having a value of -1/2 for all materials is not supported by the data.

3. Slopes of the log ϵ_T versus log N relationships range from -0.22 to -0.43. It appears that a slope of -1/3 represents a good approximation for all of the materials.

4. High strength materials such as HY-230 steel and 7079-T6 aluminum can fail in less than 10,000 cycles in the absence of apparent plastic strain. When plastic strain is present, failure of these two materials occurs as instantaneous fracture under the conditions of the test.

5. Cycle pattern, i.e., saw-tooth or square-wave, has little effect on ϵ_T and S_R versus N relationships. On the other hand, approximately a 50% decrease in life was observed for the square-wave pattern as compared to the saw-tooth pattern on the basis of ϵ_P.

6. Weld metal *per se* appears to have little or no effect on the low-cycle fatigue behavior of HY-100 steel.

7. Mechanical notches cause a decrease in fatigue life for all parameters. On the basis of ϵ_T and S_R, the decrease occurs as a constant percentage reduction.

8. The effect of salt-water corrosion on the low-cycle fatigue of HY-100 steel is similar to that of mechanical notches. On the basis ϵ_T the life in salt water is about 50% of that in air. The corrosive effect of salt water increases with decreasing ϵ_T, but seems to be little affected by cycle time *per se*.

Considerable work is currently under way in the area of design for low-cycle fatigue. Much remains to be done, however, in utilizing data of the type described herein in the design of complex structures. It would appear from this investigation that a design approach based on total strain range would be more general and practical than an approach based on either plastic strain range or nominal reversed stress.

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Table 1
Chemical Composition and Properties of Materials Investigated

Material	Plate Thickness in.	Approximate Chemical Composition, %														Tensile Properties							
		C	Mn	Si	Cr	Ni	Mo	Cu	Fe	Mg	Zn	Al	Ti	V	Others	YS (0.2% Off.) psi	UTS psi	Elong in 2 in., %	Red. of Area, %	E(1) 10^6 psi	$\bar{\epsilon}_f$(2) in/in	n(3)	K(4) psi
Steels:																							
HT	2	0.10	1.30	0.19	0.04	0.01	0.02	0.22	Bal	-	-	-	0.01	0.05	-	41,000(5)	67,000	36	66	30	1.1	0.236	120,000
HY-80	2	0.13	0.23	0.20	1.73	2.95	0.38	-	Bal	-	-	-	-	-	-	88,000	105,000	28	74	30	1.2	0.155	168,000
HY-80 (Cast)	-	0.19	0.64	0.39	1.47	3.24	0.48	-	Bal	-	-	-	-	-	-	85,000	107,000	28	66	30	1.2	0.153	166,000
HY-100	2	0.17	0.25	0.20	1.81	3.09	0.42	-	Bal	-	-	-	-	-	-	114,000	127,000	22	70	30	1.2	0.126	197,000
HY-150	2	0.16	0.31	0.22	1.40	3.04	0.42	0.20	Bal	-	-	-	-	-	-	152,000	160,000	16	60	30	0.9	0.051	193,000
HY-230	1	0.025	<0.05	0.08	-	18.6	4.6	-	Bal	-	-	0.07	0.22	-	Co 6.9	230,000	240,000	10	46	27	0.6	0.040	300,000
Aluminum Alloys:																							
5086-H112	60	-	0.45	0.07	0.09	-	-	0.06	0.17	4.07	<0.01	Bal	<0.01	-	-	30,000	47,000	18	36	10	0.4	0.250	92,000
5086-H32	2	-	0.45	0.08	0.08	-	-	0.05	0.13	4.00	<0.01	Bal	<0.01	-	-	31,000	43,000	19	41	10	0.5	0.167	70,000
5456-H311	60	-	0.73	0.10	0.08	-	-	0.06	0.23	5.05	<0.01	Bal	<0.01	-	-	33,000	55,000	14	24	10	0.3	0.250	110,000
5456-H321	3	-	0.74	0.09	0.09	-	-	0.03	0.10	5.70	0.10	Bal	<0.01	-	-	29,000	47,000	26	30	10	0.4	0.225	84,000
6061-T6	3	-	0.06	0.52	0.18	-	-	0.15	0.20	0.80	0.02	Bal	0.06	-	-	41,000	45,000	13	32	10	0.4	0.092	61,000
7079-T6	3	-	0.21	0.09	0.15	-	-	0.41	0.14	3.60	4.00	Bal	0.07	-	-	68,000	75,000	15	30	10	0.4	0.117	108,000
Nickel Alloys:																							
Monel	1 7/8	0.17	1.02	0.18	-	66.96	-	30.50	1.14	-	-	0.009	-	-	-	50,000	85,000	42	68	26	1.2	0.262	148,000
K-Monel	1	0.16	0.54	0.19	-	65.21	-	29.98	0.67	-	-	2.83	-	-	-	125,000	170,000	24	36	26	0.5	0.230	310,000
Inconel	2 1/2	0.04	0.13	0.20	15.66	76.94	-	0.07	6.93	-	-	-	-	-	-	33,100	88,000	51	62	31	1.0	0.555	223,000
Inconel-718	1	0.06	0.30	0.33	18.85	54.30	2.95	0.08	16.90	-	-	0.58	1.03	-	Cb+Ta 4.59	147,000	179,000	24	30	30	0.4	0.121	257,000
Nionel	1	0.03	0.69	0.31	20.55	40.87	2.76	1.69	31.75	-	-	0.22	1.10	-	-	39,000	95,000	46	60	28	0.7	0.446	219,000
Copper Alloys:																							
70-30 Cu-Ni	1	-	0.94	-	-	29.64	-	68.55	0.61	-	0.24	-	-	-	-	20,000	58,000	49	70	22	1.2	0.206	116,000
Gun-metal	1	-	-	-	-	0.72	-	87.25	0.02	-	3.51	-	-	-	Sn 8.44	16,000	39,000	44	39	15	0.5	0.450	83,000
Superston 40	1	-	12.51	-	-	2.15	-	74.65	3.30	-	-	7.40	-	-	-	43,000	85,000	20	24	18	0.3	0.256	154,000

(1) E = Modulus of Elasticity
(2) $\bar{\epsilon}_f$ = True Fracture Strain
(3) n = Strain Hardening Exponent
(4) K = Strength Coefficient
(5) Yield Point

YS - Yield Strength
UTS - Ultimate Tensile Strength
Elong - Elongation
Red. - Reduction
Off. - Offset

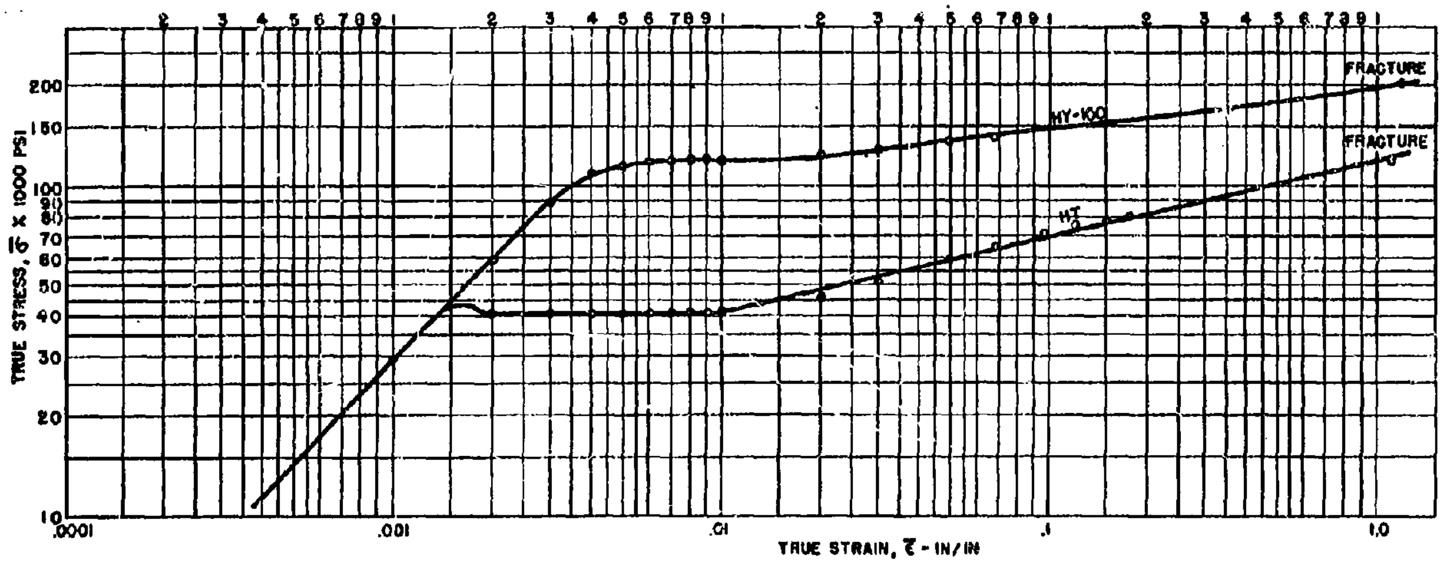


FIGURE 1

TRUE STRESS-TRUE STRAIN DIAGRAMS FOR HT AND HY-100 STEELS

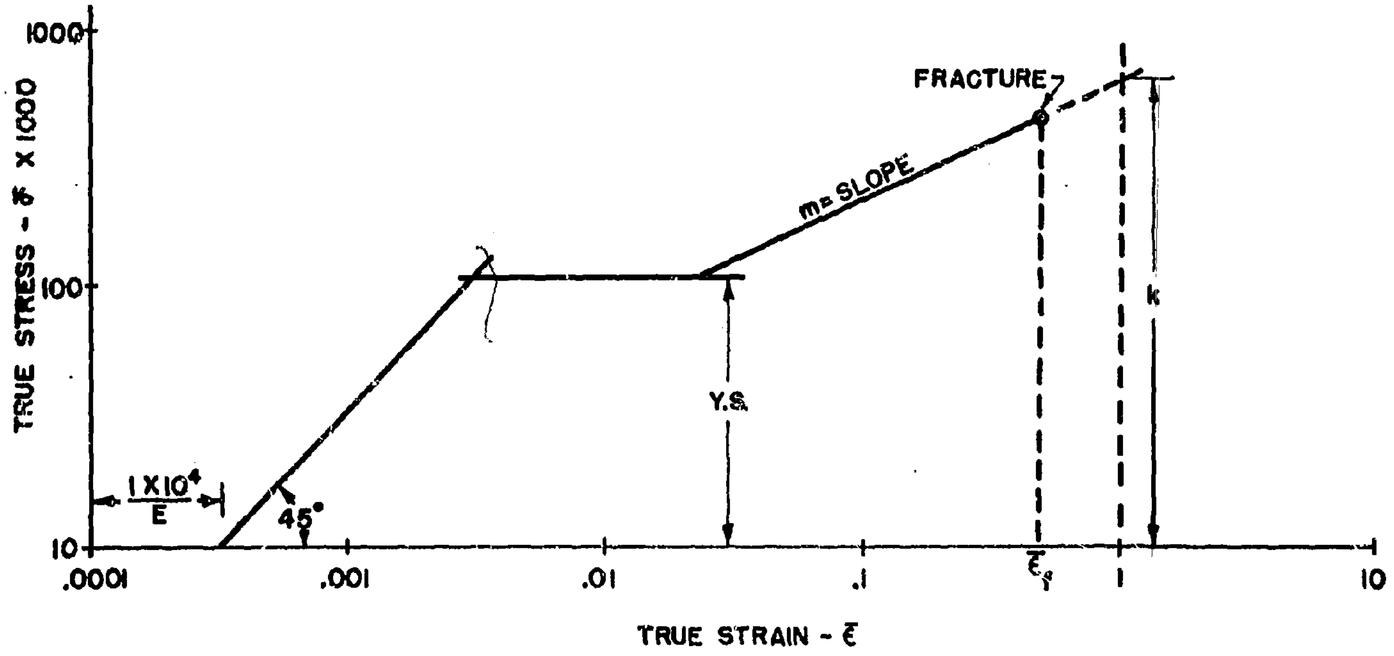
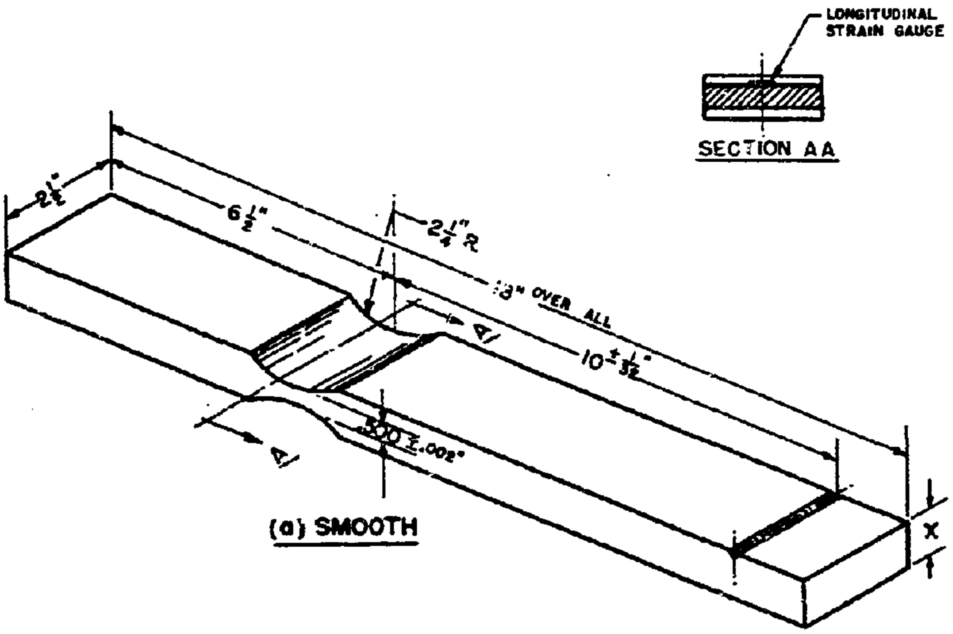
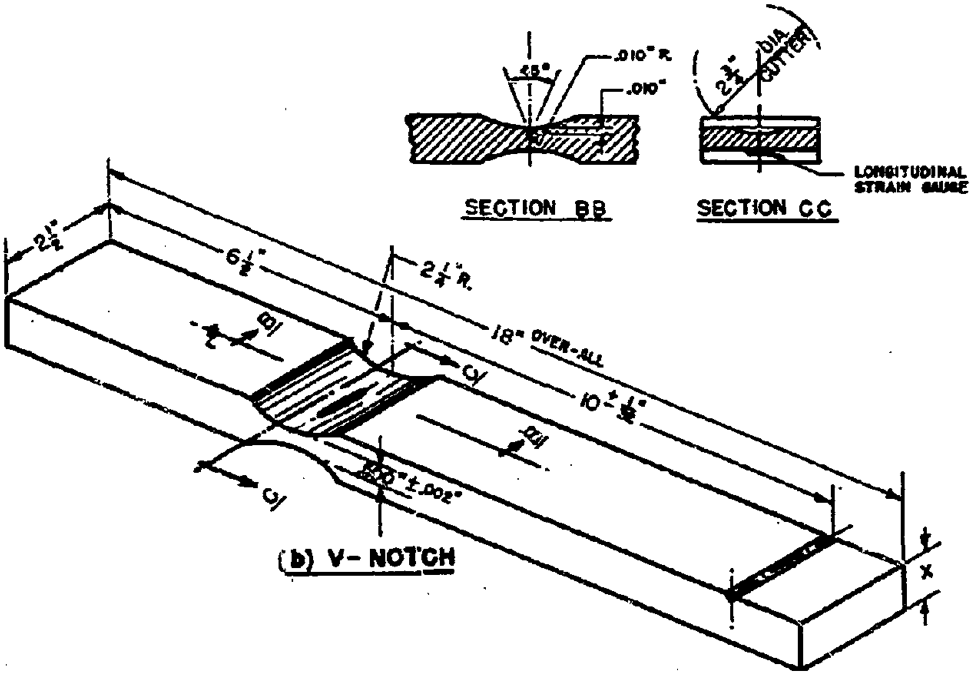


Figure 2

Construction of True Stress-True Strain Diagram
From Tensile Data in Table 1

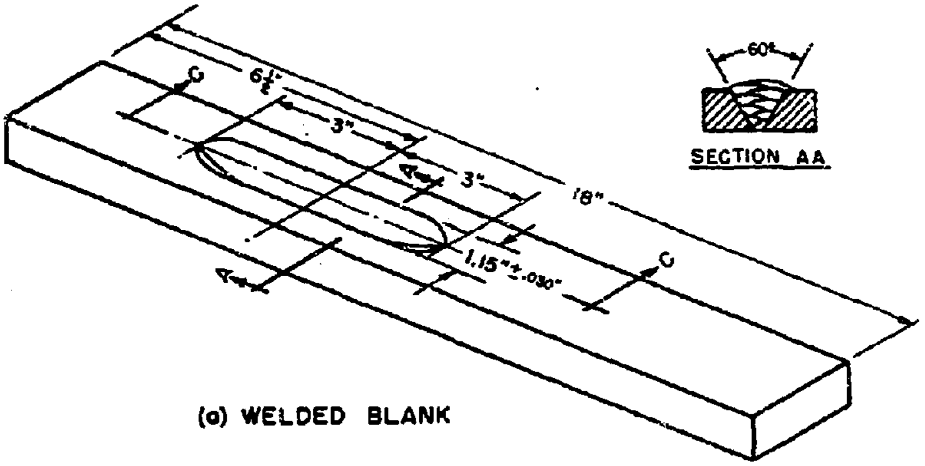


(a) SMOOTH

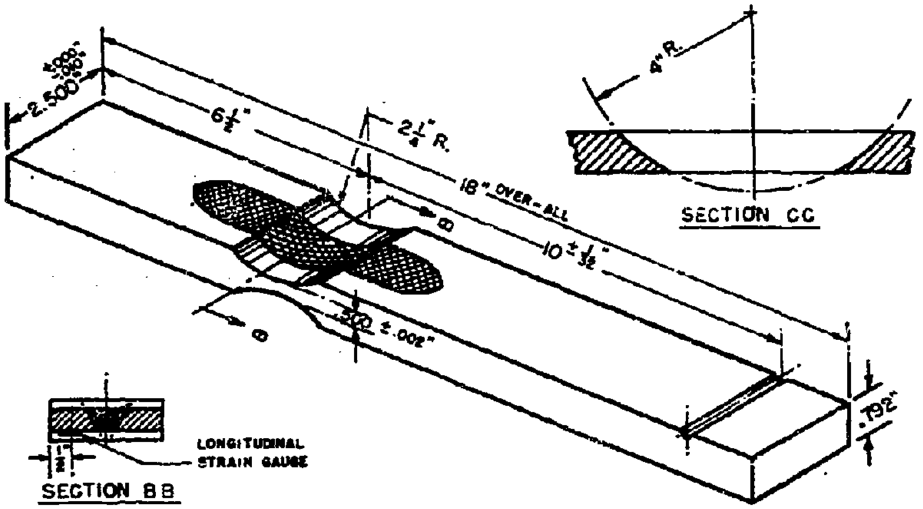


(b) V-NOTCH

FIGURE 3
LOW-CYCLE FATIGUE SPECIMENS



(a) WELDED BLANK



(b) FINISHED SPECIMEN

FIGURE 4

WELDED LOW-CYCLE FATIGUE SPECIMEN

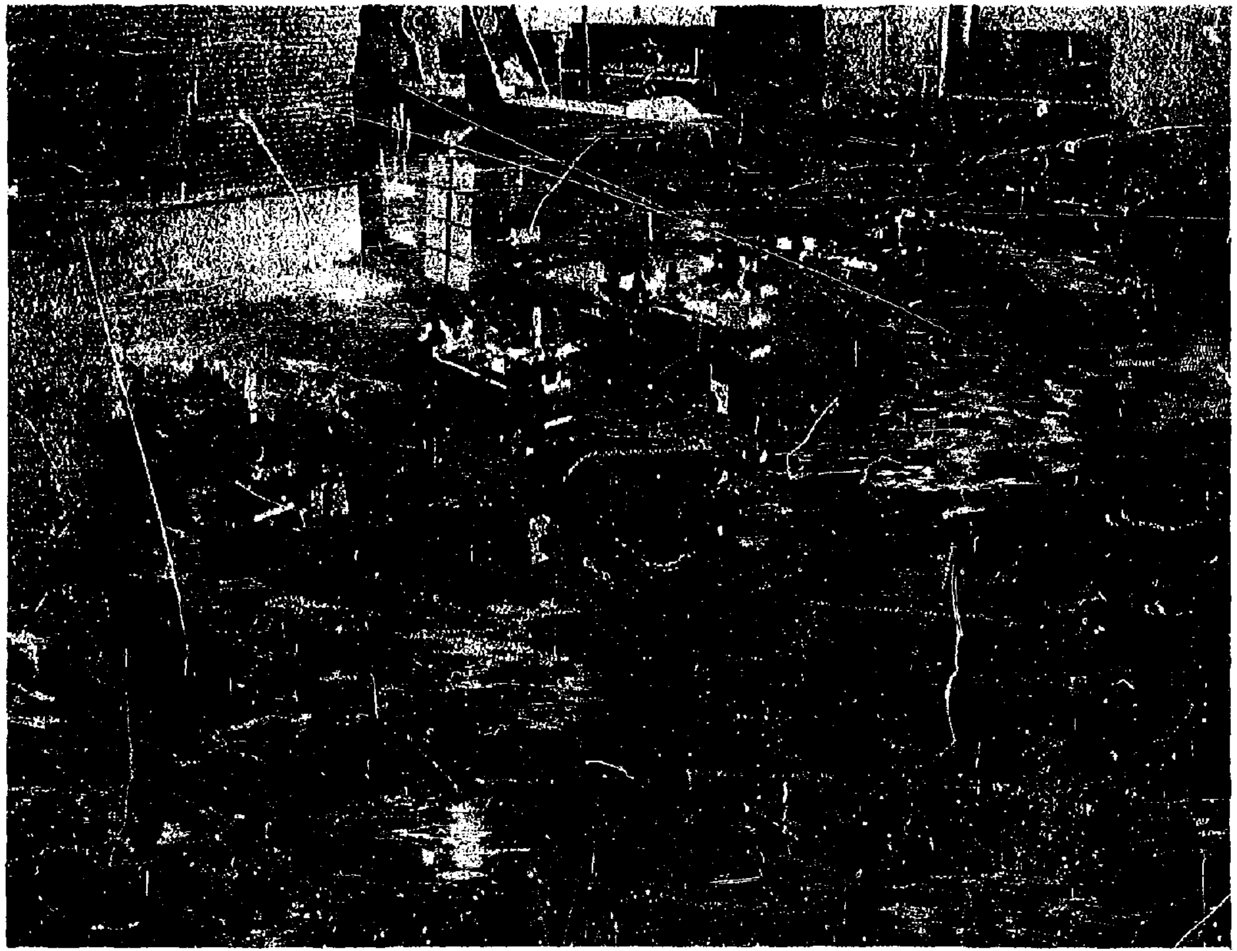


FIGURE 5
LOW-CYCLE FATIGUE TEST MACHINES

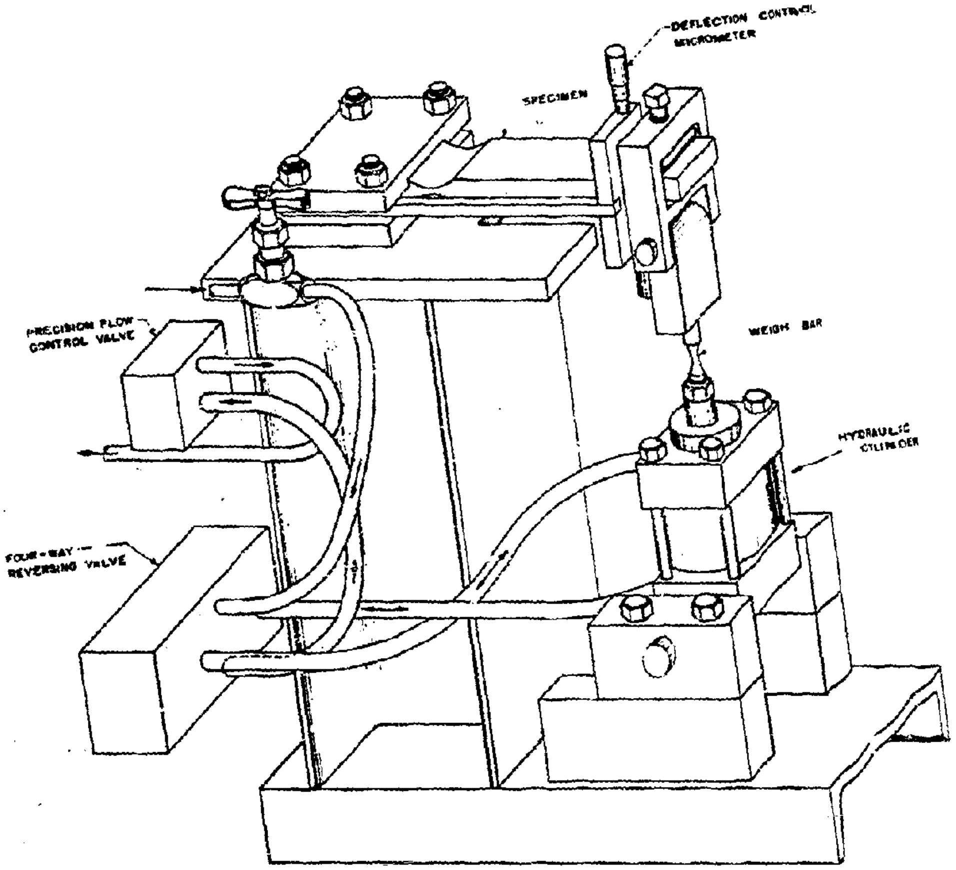


FIGURE 6

LOW-CYCLE FATIGUE TESTING MACHINE

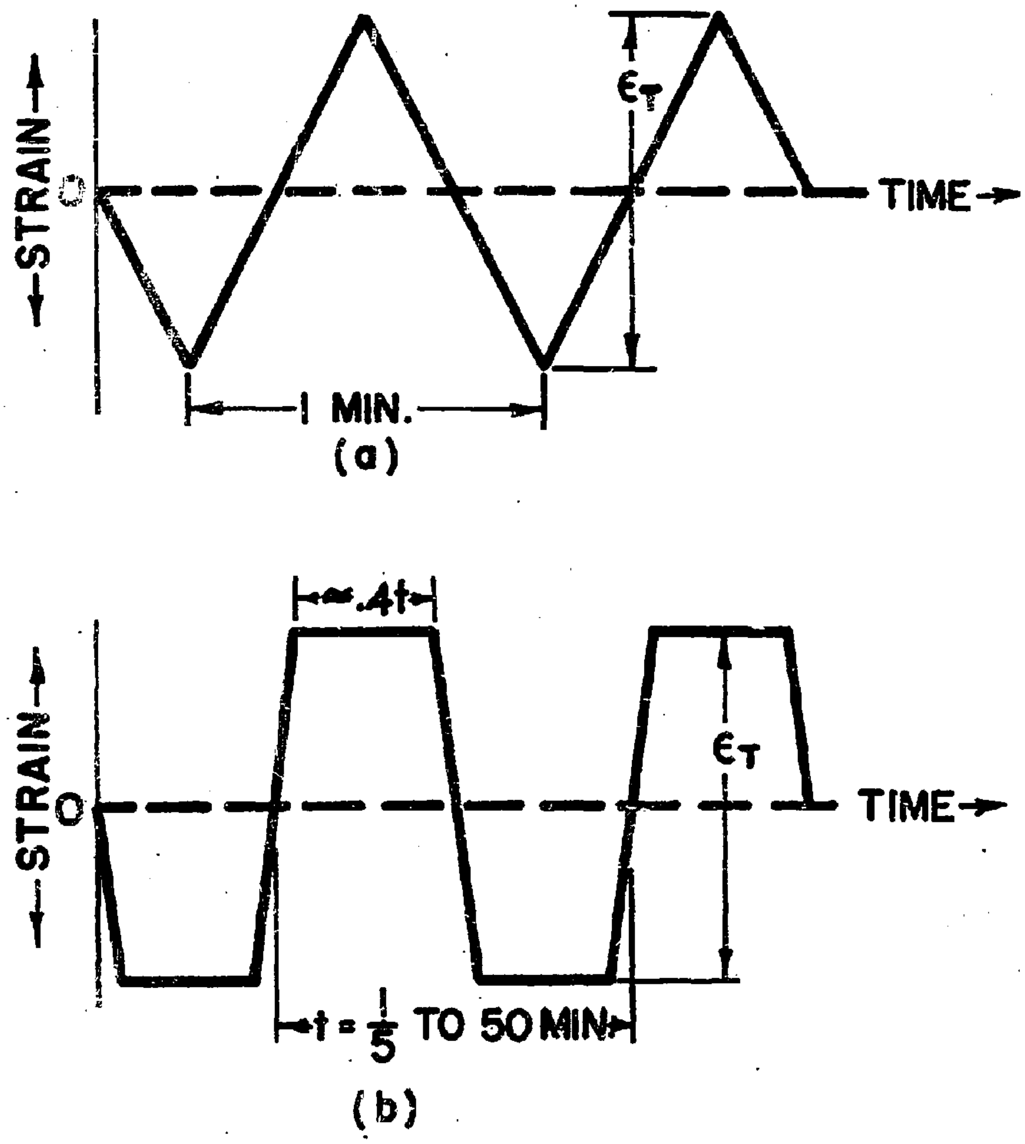


FIGURE 7
STRAIN VS TIME RELATIONSHIPS FOR LOW-CYCLE FATIGUE TESTS

M_T - TOTAL MOMENT RANGE
M_R - MAXIMUM REVERSED MOMENT
ϵ_T - TOTAL STRAIN RANGE
ϵ_R - MAXIMUM REVERSED STRAIN
ϵ_P - PLASTIC STRAIN RANGE

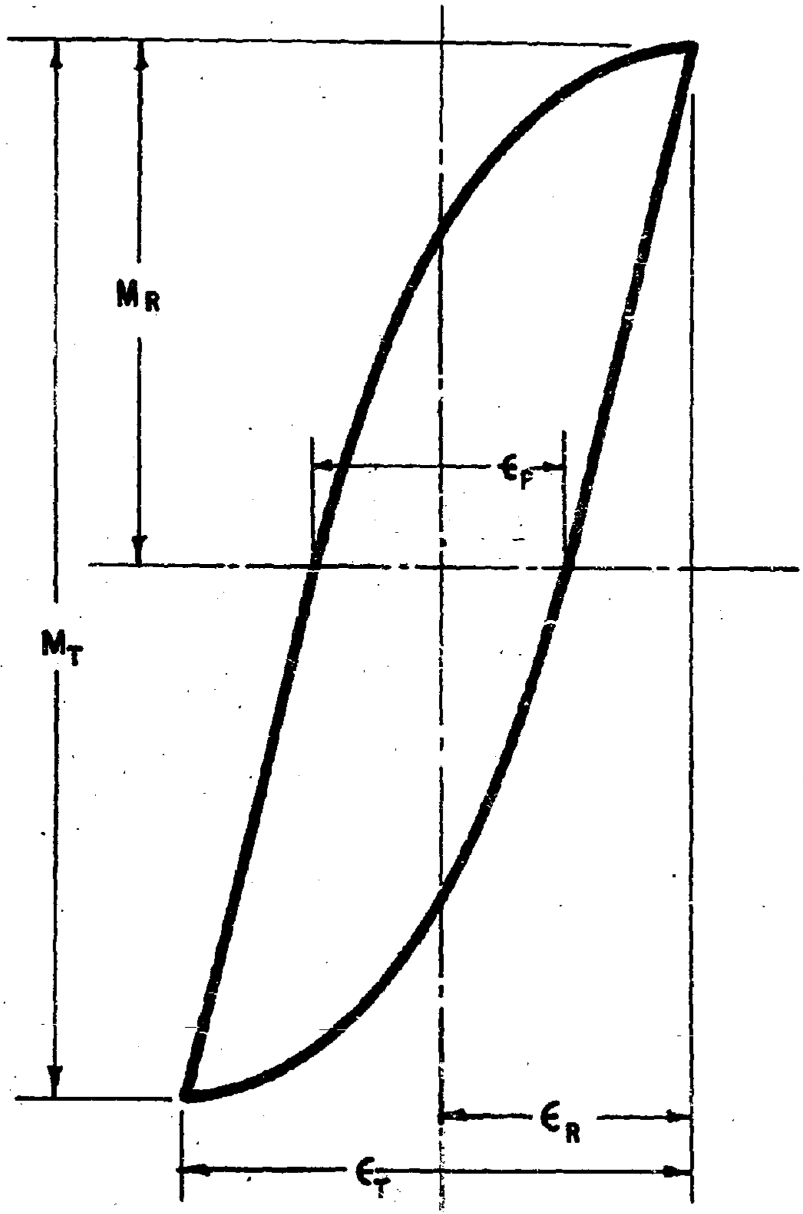
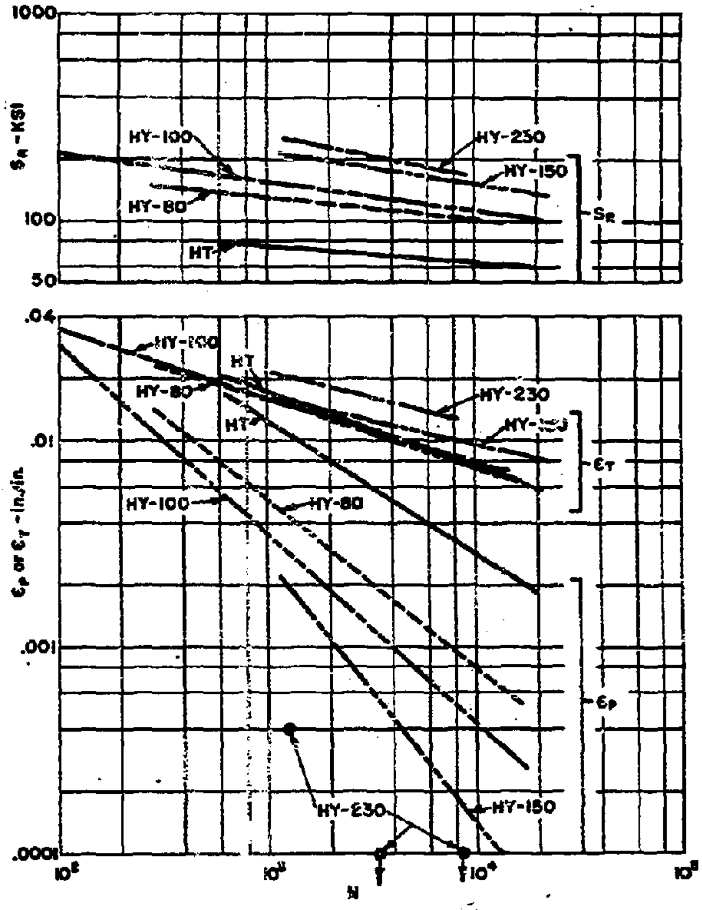


FIGURE 8
TYPICAL MECHANICAL HYSTERESIS LOOP AND PARAMETERS



CONSTANTS FOR $VN^K = C$

MATERIAL	NO. OF TESTS	$\epsilon_P = V$		$\epsilon_T = V$		$S_R = V$	
		K	C	K	C	K	C
HT	6	0.75	1.12	0.36	0.21	0.08	130,000
HY-80	10	0.86	1.92	0.30	0.13	0.12	287,000
HY-100	30	0.93	2.09	0.33	0.16	0.15	430,000
HY-150	3	1.28	18.85	0.24	0.08	0.17	670,000
HY-230	3	-	-	0.23	0.10	0.21	1,150,000

FIGURE 9
LOW-CYCLE FATIGUE RELATIONSHIPS FOR STEELS IN AIR
(SMOOTH SURFACE - SAWTOOTH PATTERN)

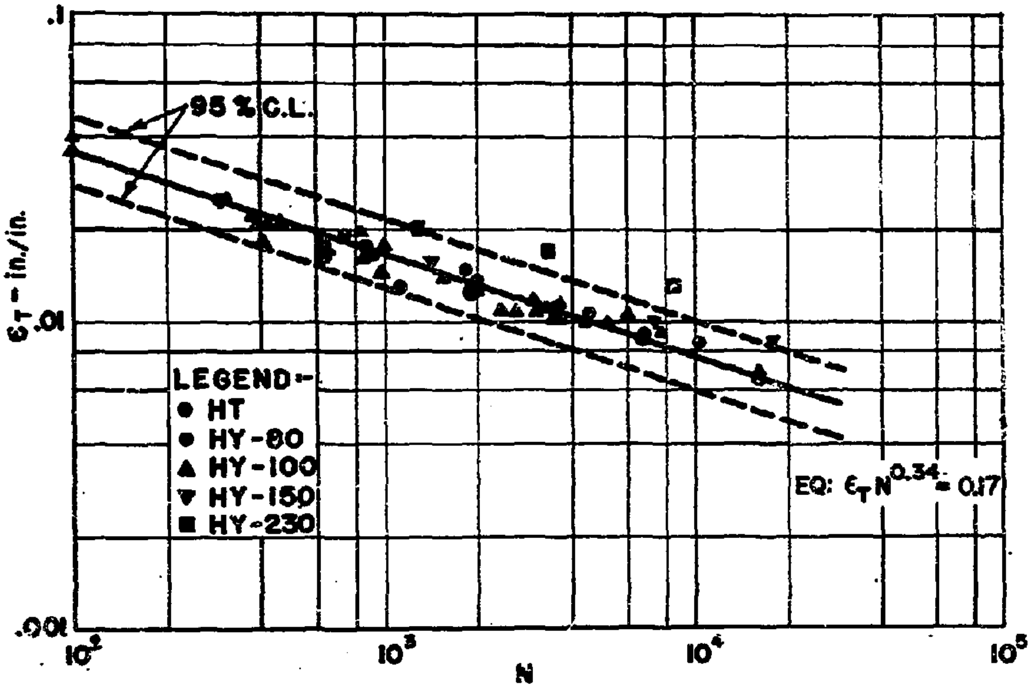
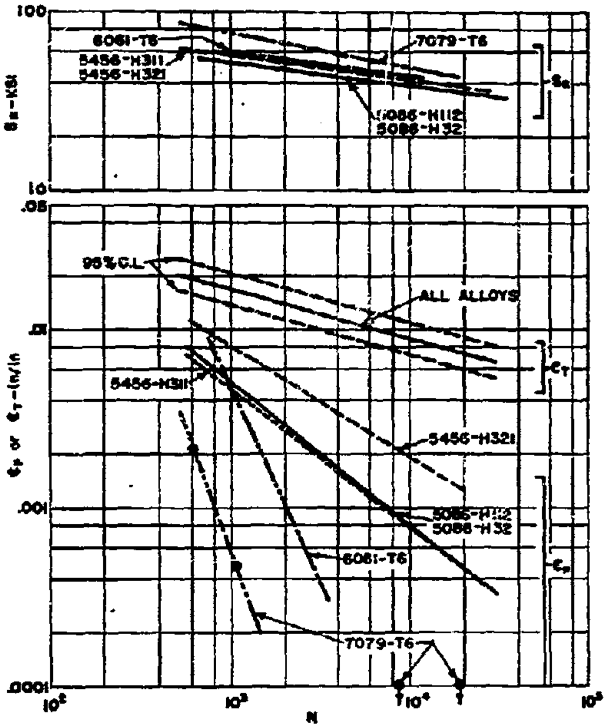


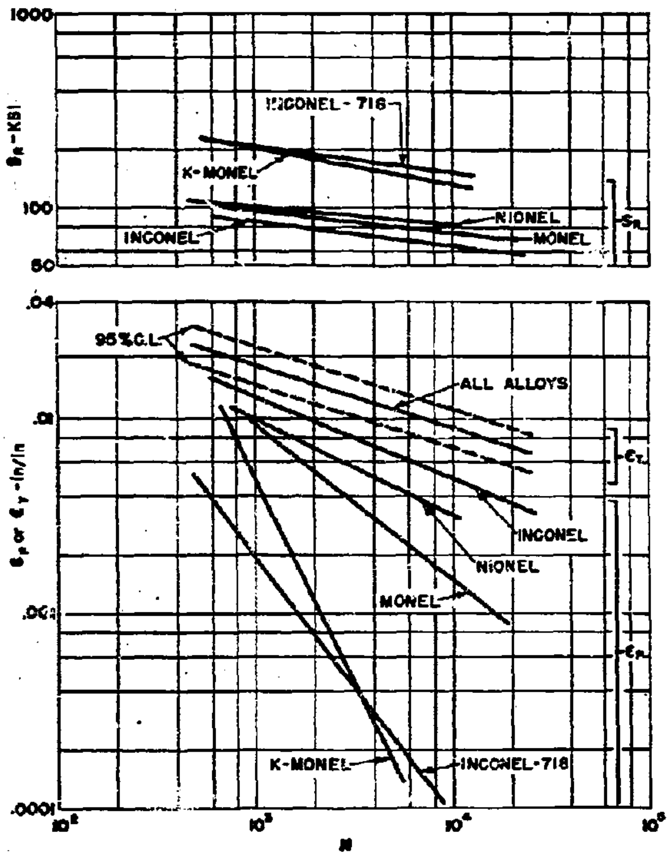
FIGURE 10
TOTAL STRAIN RANGE VS CYCLES TO FAILURE
FOR ALL STEELS IN AIR
(SMOOTH SURFACE - SAWTOOTH PATTERN)



CONSTANTS FOR $VN^K = C$

MATERIAL	NO. OF TESTS	$\epsilon_P = V$		$\epsilon_T = V$		$S_R = V$	
		K	C	K	C	K	C
5086-H112	6	0.82	1.42	0.24	0.08	0.13	132,000
5086-H32	4	0.79	1.22	0.28	0.11	0.12	122,000
5456-H311	4	0.78	0.95	0.22	0.07	0.14	151,000
5456-H321	4	0.62	0.60	0.30	0.15	0.14	150,000
6061-T6	4	2.22	21,400	0.43	0.36	0.21	284,000
7079-T6	4	2.40	10,000	0.25	0.09	0.19	289,000
ALL	26	-	-	0.28	0.11	-	-

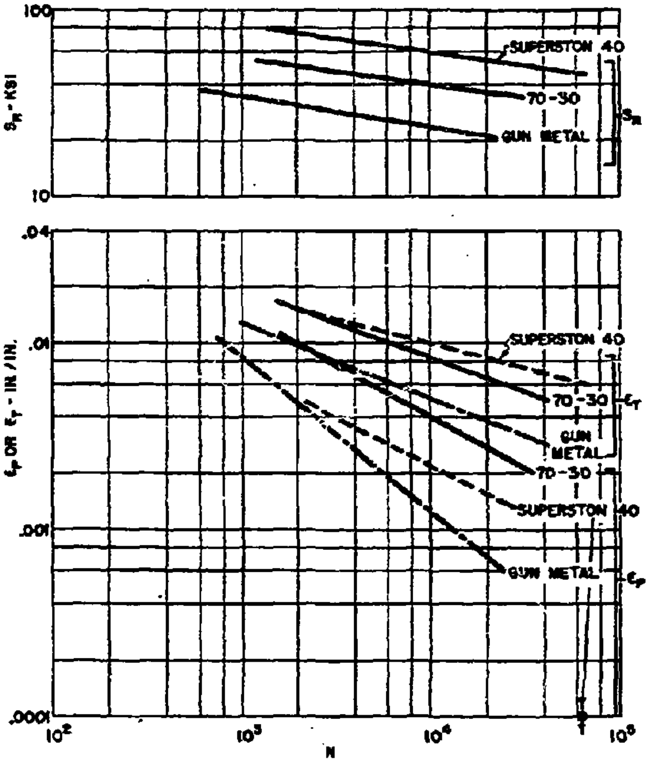
FIGURE 11
LOW-CYCLE FATIGUE RELATIONSHIPS
FOR ALUMINUM BASE ALLOYS IN AIR
(SMOOTH SURFACE - SAWTOOTH PATTERN)



CONSTANTS FOR $VN^K = C$

MATERIAL	No. OF TESTS	$\epsilon_p = V$		$\epsilon_T = V$		$S_p = V$	
		K	C	K	C	K	C
MONEL	4	0.82	2.30	0.33	0.16	0.12	217,000
K-MONEL	4	2.08	8110	0.27	0.13	0.19	782,000
INCONEL	4	0.42	0.23	0.30	0.16	0.13	202,000
INCONEL 718	4	1.35	21.0	0.22	0.08	0.13	525,000
NIONEL	4	0.49	0.30	0.29	0.10	0.09	192,000
ALL	20	-	-	0.32	0.17	-	-

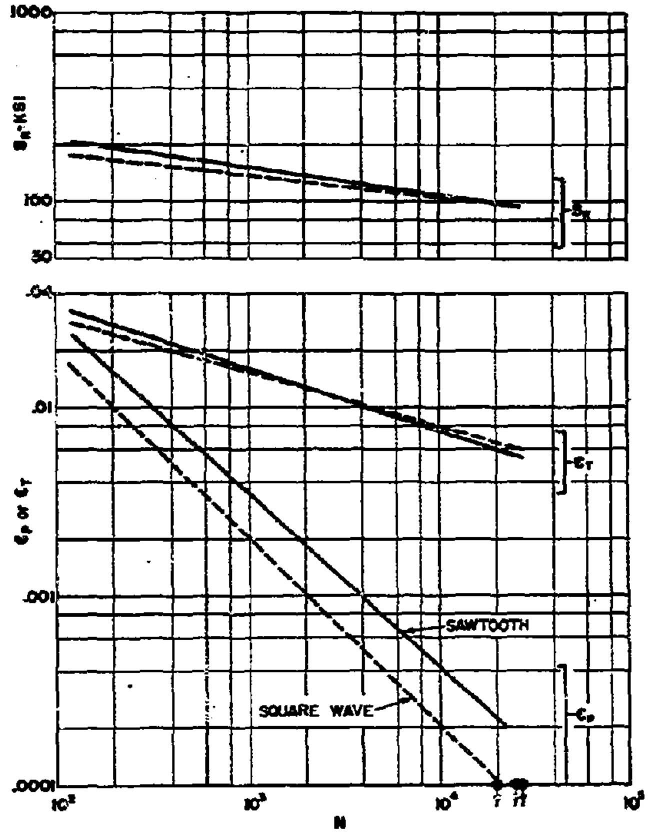
FIGURE 12
LOW-CYCLE FATIGUE RELATIONSHIPS
FOR NICKEL BASE ALLOYS IN AIR
(SMOOTH SURFACE - SAWTOOTH PATTERN)



CONSTANTS FOR $VN^K = C$

	No. of	$\epsilon_P = V$		$\epsilon_T = V$		$S_R = V$	
MATERIAL	TESTS	K	C	K	C	K	C
70-30 Cu-Ni	3	0.55	0.66	0.37	0.25	0.14	150,000
Gun Metal	3	0.82	2.37	0.41	0.22	0.16	108,000
Superston 40	4	0.51	0.24	0.26	0.11	0.14	220,000
All	10	-	-	0.35	0.21	-	-

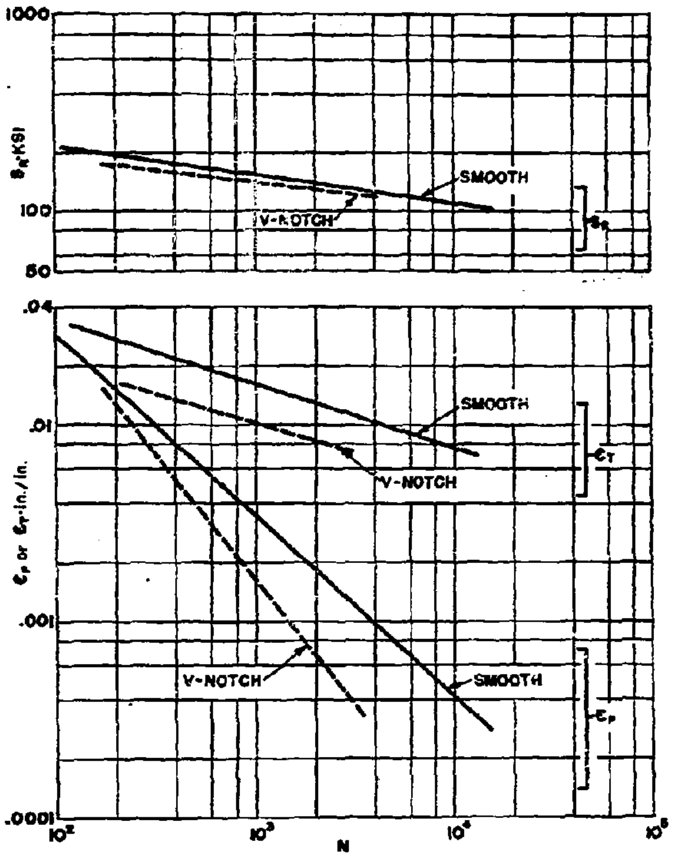
FIGURE 13
LOW-CYCLE FATIGUE RELATIONSHIPS
FOR COPPER BASE ALLOYS IN AIR
(SMOOTH SURFACE - SQUARE WAVE PATTERN)



CONSTANTS FOR $VN^K = C$

PATTERN	NO. OF TESTS	$\epsilon_P = V$		$\epsilon_T = V$		$S_R = V$	
		K	C	K	C	K	C
SAWTOOTH	30	0.93	2.09	0.33	0.16	0.15	430,000
SQUARE	11	1.00	2.04	0.29	0.11	0.12	304,000

FIGURE 14
EFFECT OF LOAD PATTERN ON LOW-CYCLE FATIGUE
OF HY-100 STEEL IN AIR
(SMOOTH SURFACE)



CONSTANTS FOR $VN^K = C$

Type	No. of Tests	$\epsilon_p = V$ K	$\epsilon_p = V$ C	$\epsilon_T = V$ K	$\epsilon_T = V$ C	$S_R = V$ K	$S_R = V$ C
Smooth	30	0.93	2.09	0.33	0.16	0.15	430,000
V-Notch	17	1.28	10.68	0.33	0.12	0.12	328,000

FIGURE 15
EFFECT OF NOTCHES ON LOW-CYCLE FATIGUE
OF HY-100 STEEL IN AIR
(SAWTOOTH PATTERN)

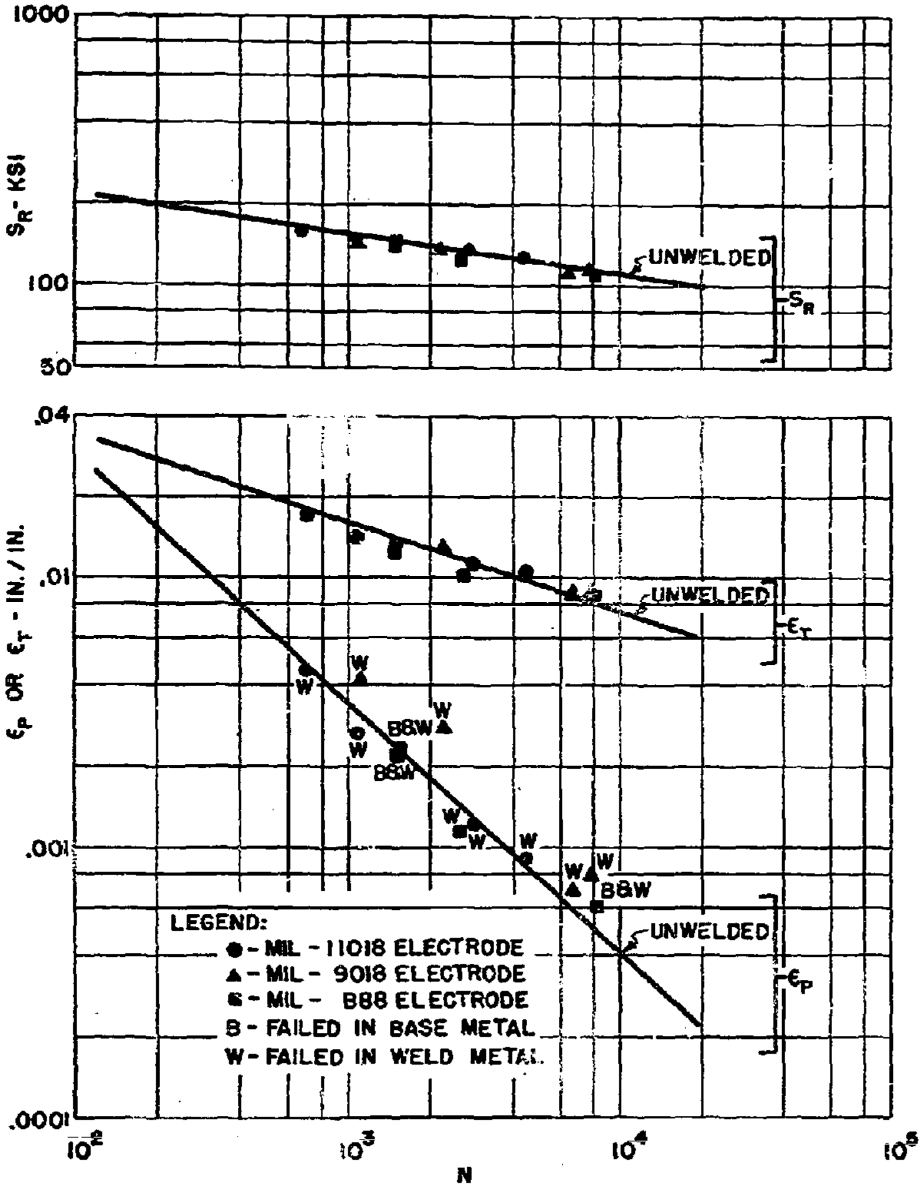
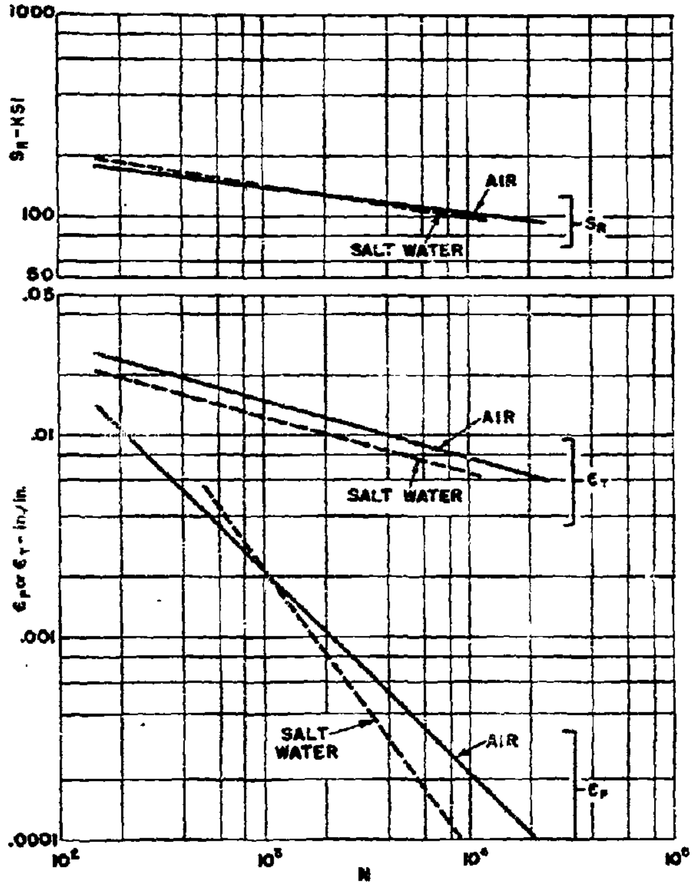


FIGURE 16
EFFECT OF WELDMENTS ON LOW-CYCLE FATIGUE
OF HY-100 STEEL IN AIR
(SMOOTH SURFACE - SAWTOOTH PATTERN)



CONSTANTS FOR $VN^K = C$

ENVIRONMENT	NO. OF TESTS	$\epsilon_P = V$		$\epsilon_T = V$		$S_R = V$	
		K	C	K	C	K	C
AIR	11	1.00	2.04	0.29	0.11	0.12	304,000
SALT WATER	31	1.42	4.05	0.27	0.08	0.16	428,000

FIGURE 17
EFFECT OF SALT WATER
ON THE LOW-CYCLE FATIGUE OF HY-100 STEEL
(SMOOTH SURFACE - SQUARE WAVE)

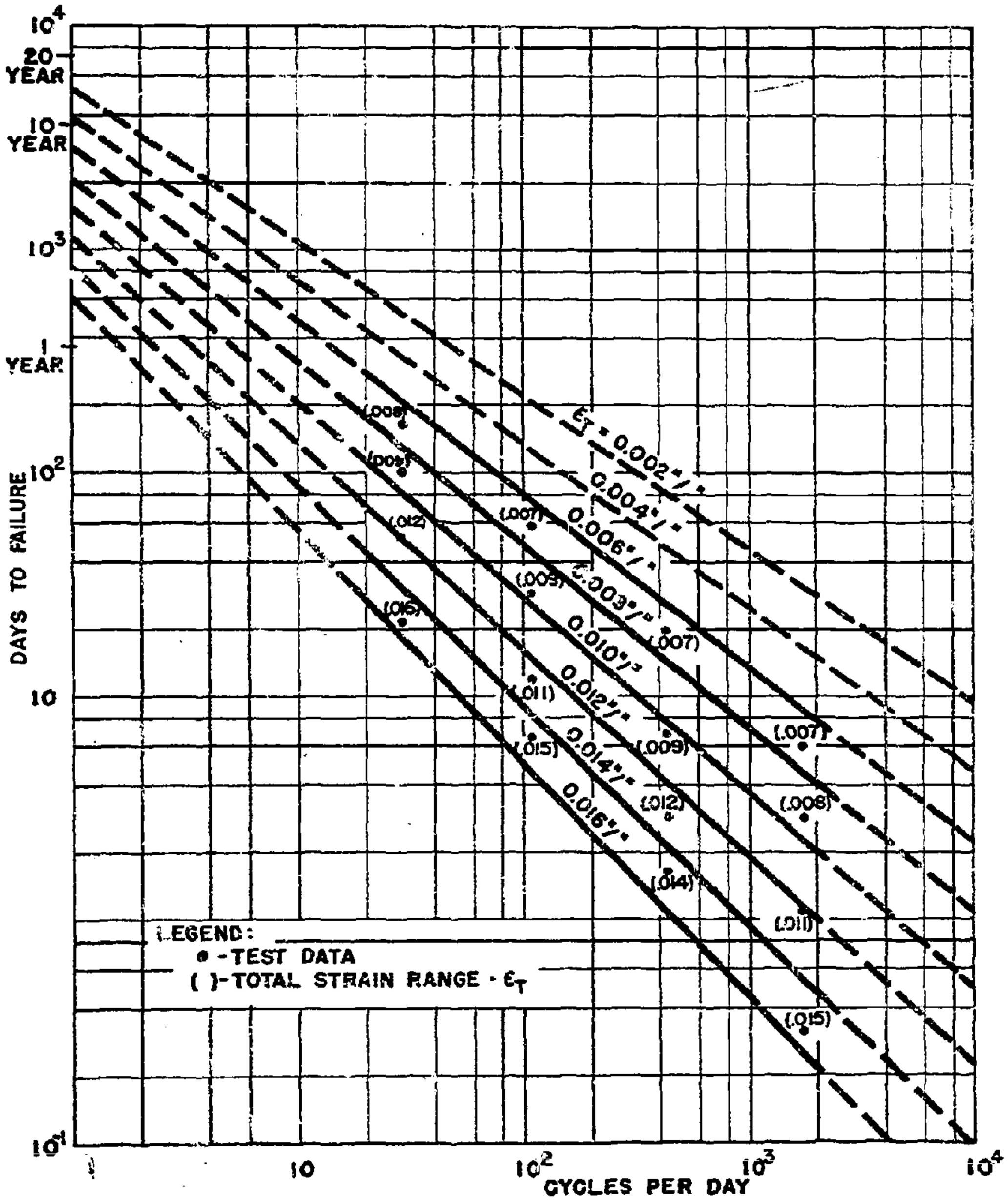


FIGURE 18
EFFECT OF CYCLE FREQUENCY AND TOTAL STRAIN RANGE
ON THE LOW-CYCLE FLEXURAL FATIGUE LIFE OF HY-100 STEEL IN SALT WATER
(SMOOTH SURFACE - SQUARE WAVE PATTERN)

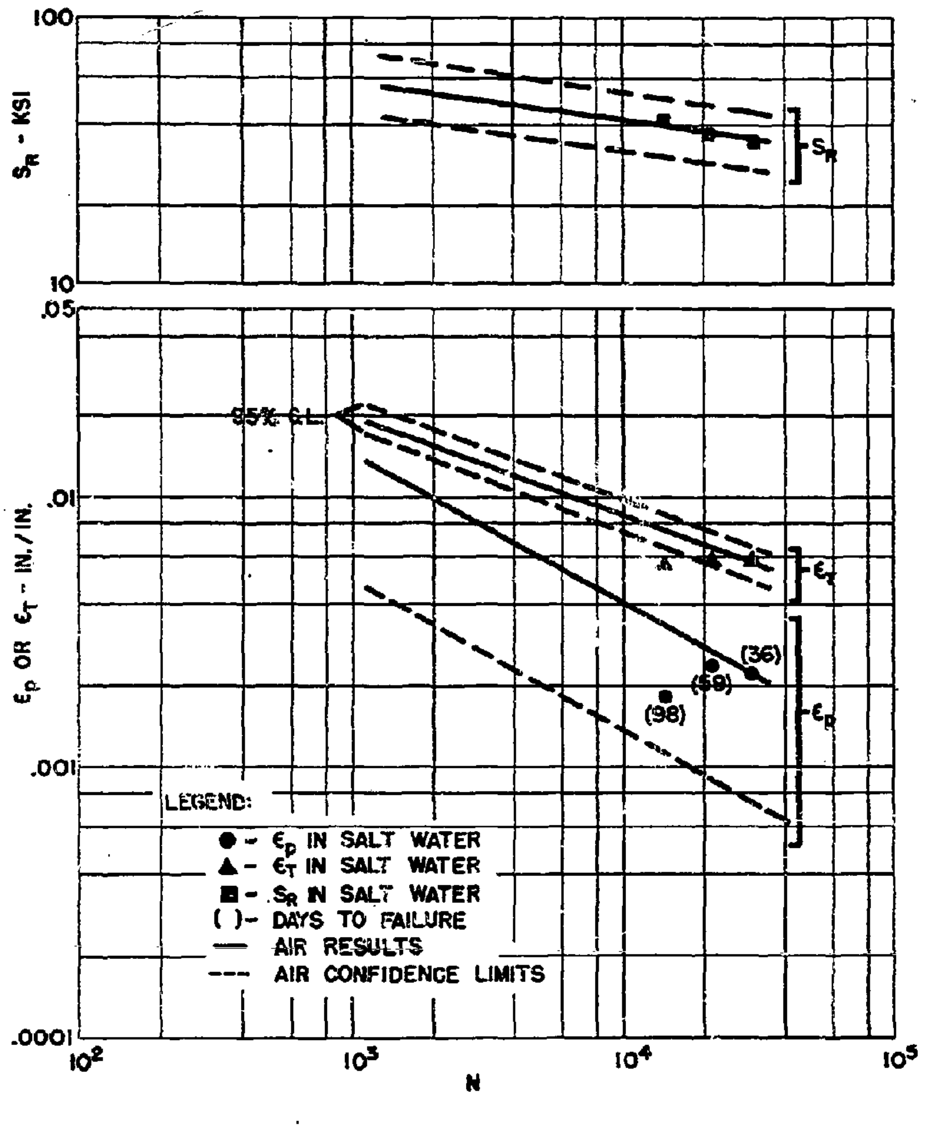


FIGURE 19
LOW-CYCLE FATIGUE RELATIONSHIPS
FOR 70-30 CU-NI IN AIR AND SALT WATER
(SMOOTH SURFACE - SQUARE WAVE PATTERN)

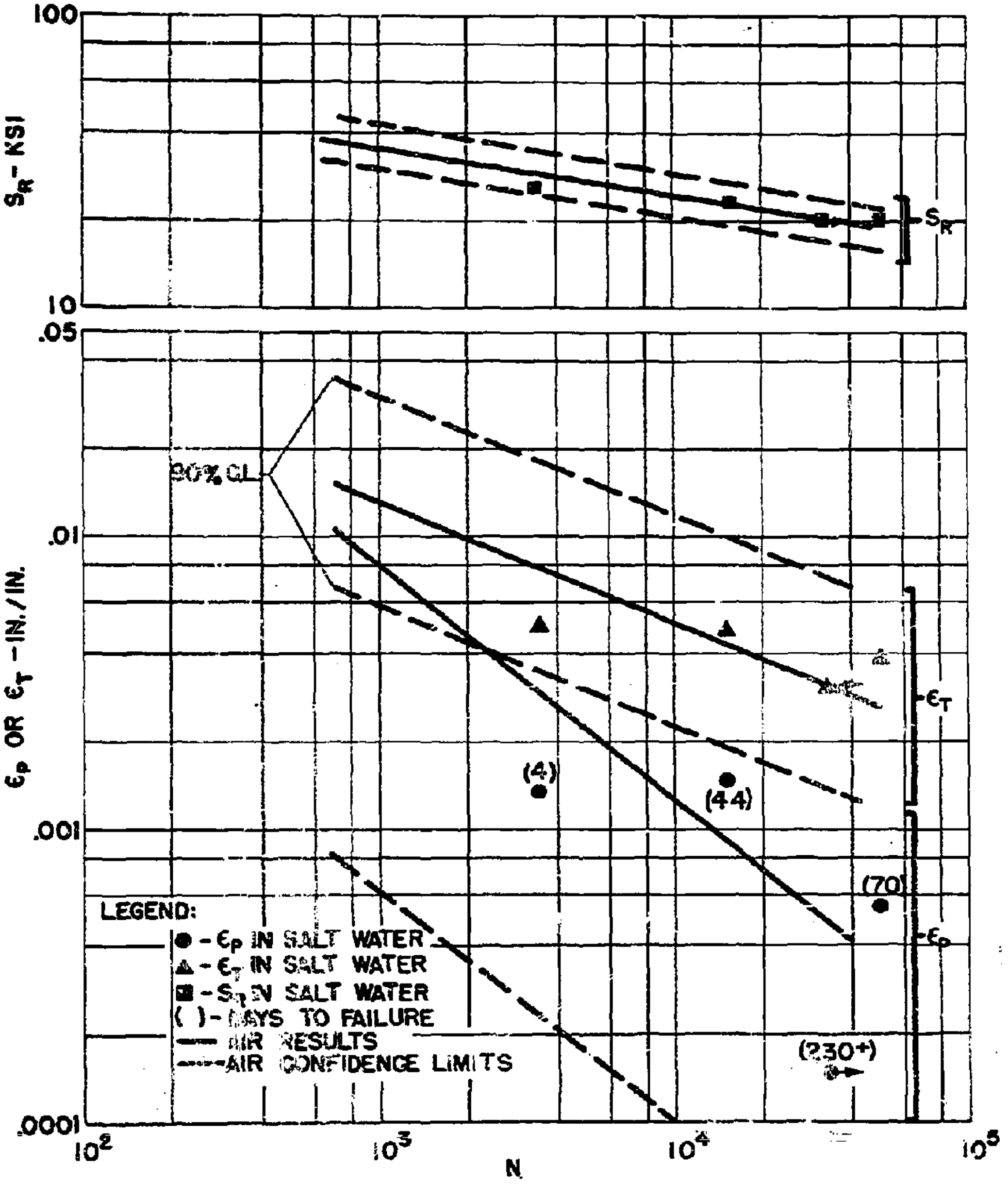


Figure 20
Low-Cycle Fatigue Relationships
for Gun Metal in Air and Salt-Water
(Smooth Surface - Square Wave Pattern)

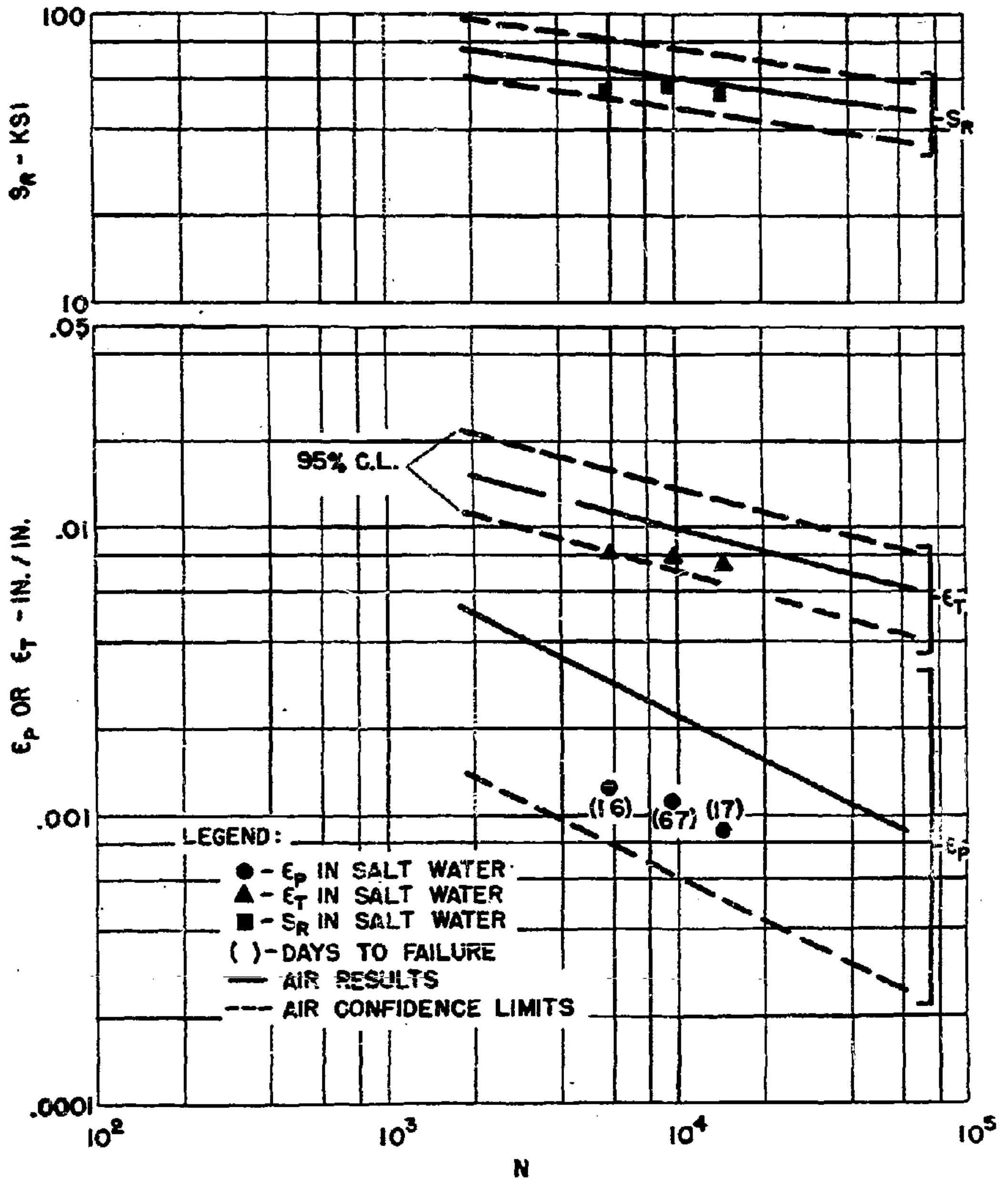


Figure 21
Low-Cycle Fatigue Relationships
for Superston 40 in Air and Salt Water
(Smooth Surface - Square Wave Pattern)

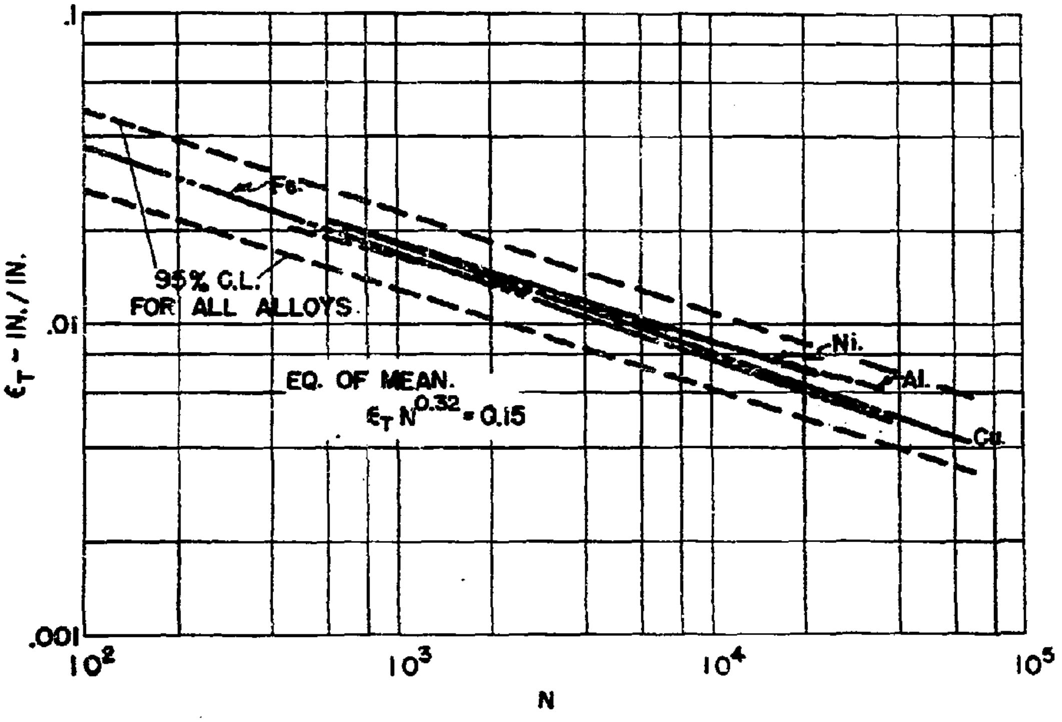


FIGURE 22
TOTAL STRAIN RANGE VS CYCLES TO FAILURE
FOR ALL ALLOYS IN AIR
(SMOOTH SURFACE - SAWTOOTH PATTERN)

APPENDIX A

TABULATION OF DATA

IRON BASE ALLOYS

MATERIAL	TYPE OF SPECIMEN	TEST ENVIRONMENT	CYCLES TO FAILURE N	EP IN/IN	ET IN/IN	WT IN-LB	SR PSI	CYCLES PER MINUTE	CYCLE PATTERN	SPECIMEN DIRECTION
HT	SMOOTH	AIR	749	0.01300	0.01900	16000	76900	1.000	SAW	T
HT	SMOOTH	AIR	1857	0.00910	0.01480	15250	73200	1.000	SAW	L
HT	SMOOTH	AIR	1990	0.00760	0.01310	14500	67700	1.000	SAW	T
HT	SMOOTH	AIR	4604	0.00550	0.01060	14250	68500	1.000	SAW	L
HT	SMOOTH	AIR	6671	0.00400	0.00880	13500	64900	1.000	SAW	T
HT	SMOOTH	AIR	16430	0.00180	0.00630	12750	61200	1.000	SAW	L
HT	V-NOTCH	AIR	503	0.01060	0.01650	15500	74500	1.000	SAW	T
HT	V-NOTCH	AIR	1605	0.00390	0.00880	14000	67200	1.000	SAW	T
HT	V-NOTCH	AIR	3116	0.00180	0.00640	12600	60600	1.000	SAW	L
HY-80	SMOOTH	AIR	300	0.01360	0.02420	29500	142000	1.000	SAW	T
HY-80	SMOOTH	AIR	641	0.00750	0.01804	28500	137000	1.000	SAW	L
HY-80	SMOOTH	AIR	652	0.00580	0.01610	28000	134600	1.000	SAW	L
HY-80	SMOOTH	AIR	867	0.00650	0.01690	27750	132200	1.000	SAW	T
HY-80	SMOOTH	AIR	903	0.00620	0.01654	27700	133200	1.000	SAW	L
HY-80	SMOOTH	AIR	1122	0.00330	0.01280	24900	119700	1.000	SAW	L
HY-80	SMOOTH	AIR	1910	0.00350	0.01276	25000	120200	1.000	SAW	L
HY-80	SMOOTH	AIR	1944	0.00316	0.01254	25500	122600	1.000	SAW	L
HY-80	SMOOTH	AIR	6919	0.00110	0.00900	22000	105700	1.000	SAW	T
HY-80	SMOOTH	AIR	10220	0.00062	0.00830	20000	96100	1.000	SAW	T
HY-80	V-NOTCH	AIR	191	0.01000	0.02150	28500	137000	1.000	SAW	T
HY-80	V-NOTCH	AIR	300	0.00394	0.01030	24250	115600	1.000	SAW	L
HY-80	V-NOTCH	AIR	444	0.00656	0.01670	27950	134400	1.000	SAW	L
HY-80	V-NOTCH	AIR	568	0.00592	0.01750	22500	109400	1.000	SAW	L
HY-80	V-NOTCH	AIR	2390	0.00110	0.00910	21500	103400	1.000	SAW	T
HY-80	WELDED 11018 ELECT.	AIR	665	0.00424	0.01436	28750	138200	1.000	SAW	L
HY-80	WELDED 11018 ELECT.	AIR	958	0.00400	0.01332	26850	129100	1.000	SAW	L
HY-80	WELDED 11018 ELECT.	AIR	3219	0.00204	0.01084	23700	113900	1.000	SAW	L
HY-80	WELDED 11018 ELECT.	AIR	4735	0.00150	0.00970	22000	105800	1.000	SAW	L
HY-80	WELDED 9018 ELECTRODE	AIR	1037	0.00416	0.01368	25500	122600	1.000	SAW	L
HY-80	WELDED 9018 ELECTRODE	AIR	1578	0.00348	0.01274	26300	126400	1.000	SAW	L
HY-80	WELDED 9018 ELECTRODE	AIR	8203	0.00120	0.00858	20900	100500	1.000	SAW	L
HY-80	WELDED 9018 ELECTRODE	AIR	9430	0.00116	0.00738	20300	97600	1.000	SAW	L
HY-80	WELDED B88A632-ELECT	AIR	448	0.00340	0.01344	27650	132900	1.000	SAW	L
HY-80	WELDED B88A632-ELECT	AIR	755	0.00250	0.01170	26900	129300	1.000	SAW	L
HY-80	WELDED B88A632-ELECT	AIR	1178	0.00254	0.01228	27900	134100	1.000	SAW	L
HY-80	WELDED B88A632-ELECT	AIR	2968	0.00150	0.01000	22750	109400	1.000	SAW	L
HY-80(CAST)	SMOOTH	AIR	1850	0.00308	0.01180	24250	116400	1.000	SAW	CAST
HY-80(CAST)	SMOOTH	AIR	11032	0.00046	0.00685	19500	93600	1.000	SAW	CAST
HY-80(CAST)	SMOOTH	SALT WATER	1456	0.00330	0.01215	23500	112800	1.000	SAW	CAST

IRON BASE ALLOYS

MATERIAL	TYPE OF SPECIMEN	TEST ENVIRONMENT	CYCLES TO FAILURE N	EP IN/IN	ET IN/IN	PT IN-LB	SR PSI	CYCLES PER MINUTE	CYCLE PATTERN	SPECIM DIRECTI
HY-80(CAST)	SMOOTH	SALT WATER	1921	0.00166	0.00988	23200	111400	1.000	SAW	CAST
HY-80(CAST)	SMOOTH	SALT WATER	2952	0.00105	0.00830	21900	103200	1.000	SAW	CAST
HY-80(CAST)	SMOOTH	SALT WATER	3381	0.00074	0.00762	19800	95000	1.000	SAW	CAST
HY-80(CAST)	SMOOTH	SALT WATER	9436	0.00022	0.00653	18250	87600	1.000	SAW	CAST
HY-100	SMOOTH	AIR	100	0.02360	0.03600	37500	180000	1.000	SAW	L
HY-100	SMOOTH	AIR	100	0.02350	0.03950	43500	209100	1.000	SAW	L
HY-100	SMOOTH	AIR	345	0.01004	0.02336	35250	169500	1.000	SAW	T
HY-100	SMOOTH	AIR	387	0.00820	0.02200	36000	173100	1.000	SAW	T
HY-100	SMOOTH	AIR	400	0.00796	0.02096	34500	165900	1.000	SAW	L
HY-100	SMOOTH	AIR	409	0.00592	0.01802	32500	156200	1.000	SAW	T
HY-100	SMOOTH	AIR	423	0.00740	0.02060	36000	173100	1.000	SAW	T
HY-100	SMOOTH	AIR	478	0.00760	0.02140	36500	175500	1.000	SAW	L
HY-100	SMOOTH	AIR	627	0.00540	0.01758	33100	159100	1.000	SAW	L
HY-100	SMOOTH	AIR	641	0.00458	0.01682	33900	163000	1.000	SAW	T
HY-100	SMOOTH	AIR	849	0.00510	0.01960	35000	166500	1.000	SAW	T
HY-100	SMOOTH	AIR	850	0.00430	0.01650	35000	168500	1.000	SAW	T
HY-100	SMOOTH	AIR	984	0.00460	0.01720	34000	163500	1.000	SAW	L
HY-100	SMOOTH	AIR	987	0.00362	0.01440	29250	140600	1.000	SAW	T
HY-100	SMOOTH	AIR	1542	0.00288	0.01336	29350	141100	1.000	SAW	T
HY-100	SMOOTH	AIR	1920	0.00208	0.01246	28250	135800	1.000	SAW	L
HY-100	SMOOTH	AIR	2407	0.00180	0.01095	28500	137000	1.000	SAW	T
HY-100	SMOOTH	AIR	2701	0.00106	0.01066	27900	134100	1.000	SAW	T
HY-100	SMOOTH	AIR	3102	0.00130	0.01170	30250	145500	1.000	SAW	L
HY-100	SMOOTH	AIR	3113	0.00160	0.01035	27500	132200	1.000	SAW	L
HY-100	SMOOTH	AIR	3119	0.00132	0.01072	27400	131700	1.000	SAW	L
HY-100	SMOOTH	AIR	3641	0.00096	0.01052	28000	134600	1.000	SAW	L
HY-100	SMOOTH	AIR	3645	0.00082	0.01018	26600	127900	1.000	SAW	L
HY-100	SMOOTH	AIR	3662	0.00090	0.01046	27200	130800	1.000	SAW	L
HY-100	SMOOTH	AIR	3732	0.00090	0.01150	28250	135800	1.000	SAW	T
HY-100	SMOOTH	AIR	4526	0.00080	0.01000	27000	130000	1.000	SAW	T
HY-100	SMOOTH	AIR	5301	0.00060	0.00984	27000	129800	1.000	SAW	L
HY-100	SMOOTH	AIR	6250	0.00100	0.01050	28250	137000	1.000	SAW	L
HY-100	SMOOTH	AIR	7861	0.00030	0.00920	26750	128700	1.000	SAW	L
HY-100	SMOOTH	AIR	16029	0.00040	0.00660	17000	83300	1.000	SAW	L
HY-100	SMOOTH	AIR	178	0.00296	0.02860	29600	142000	3.000	SQ	L
HY-100	SMOOTH	AIR	769	0.00313	0.01380	30000	144000	0.067	SQ	L
HY-100	SMOOTH	AIR	1338	0.00245	0.01300	29000	139200	0.020	SQ	L
HY-100	SMOOTH	AIR	1874	0.00238	0.01260	28400	136300	0.200	SQ	L
HY-100	SMOOTH	AIR	4861	0.00027	0.00820	23000	110400	0.333	SQ	L
HY-100	SMOOTH	AIR	5085	0.00045	0.00880	24600	118300	1.000	SQ	L
HY-100	SMOOTH	AIR	7404	0.00026	0.00810	22800	109400	0.100	SQ	L
HY-100	SMOOTH	AIR	10687	0.00025	0.00700	22800	109700	1.667	SQ	L
HY-100	SMOOTH	AIR	20364	0.00001	0.00682	20350	97900	1.667	SQ	L
HY-100	SMOOTH	AIR	25087	0.00001	0.00645	19200	92400	5.000	SQ	L
HY-100	SMOOTH	AIR	26666	0.00001	0.00646	1900	91200	5.007	SQ	L

IRON BASE ALLOYS

MATERIAL	TYPE OF SPECIMEN	TEST ENVIRONMENT	CYCLES TO FAILURE N	EP IN/IN	ET IN/IN	WT IN-LB	SR PSI	CYCLES PER MINUTE	CYCLE PATTERN	SPECIMEN DIRECTION
HY-100	SMOOTH	SALT WATER	265	0.00270	0.01310	29000	159700	0.200	SQ	L
HY-100	SMOOTH	SALT WATER	520	0.00273	0.01305	31200	150000	0.200	SQ	L
HY-100	SMOOTH	SALT WATER	563	0.00460	0.01590	32500	157000	1.200	SQ	L
HY-100	SMOOTH	SALT WATER	621	0.00464	0.01560	30850	148100	0.020	SQ	L
HY-100	SMOOTH	SALT WATER	712	0.00410	0.01460	31000	149000	0.075	SQ	L
HY-100	SMOOTH	SALT WATER	719	0.00380	0.01440	31000	148800	0.300	SQ	L
HY-100	SMOOTH	SALT WATER	963	0.00140	0.01030	27500	132000	0.067	SQ	L
HY-100	SMOOTH	SALT WATER	1055	0.00280	0.01340	30500	146400	0.067	SQ	L
HY-100	SMOOTH	SALT WATER	1234	0.00088	0.01014	27350	131300	0.200	SQ	L
HY-100	SMOOTH	SALT WATER	1273	0.00214	0.01210	29750	142800	0.300	SQ	L
HY-100	SMOOTH	SALT WATER	1283	0.00185	0.01125	27850	133700	0.075	SQ	L
HY-100	SMOOTH	SALT WATER	1314	0.00227	0.01264	29400	141100	0.020	SQ	L
HY-100	SMOOTH	SALT WATER	1497	0.00224	0.01190	28800	138400	0.020	SQ	L
HY-100	SMOOTH	SALT WATER	1664	0.00075	0.01006	27900	133900	0.600	SQ	L
HY-100	SMOOTH	SALT WATER	1779	0.00065	0.00920	26000	124800	0.600	SQ	L
HY-100	SMOOTH	SALT WATER	1901	0.00170	0.01123	28250	136500	1.200	SQ	L
HY-100	SMOOTH	SALT WATER	1977	0.00130	0.01023	26600	127700	0.200	SQ	L
HY-100	SMOOTH	SALT WATER	2466	0.00042	0.00872	24700	118100	0.333	SQ	L
HY-100	SMOOTH	SALT WATER	2898	0.00046	0.00860	24500	117600	0.020	SQ	L
HY-100	SMOOTH	SALT WATER	2951	0.00106	0.00890	26700	128200	0.300	SQ	L
HY-100	SMOOTH	SALT WATER	2970	0.00050	0.00880	25000	120000	1.000	SQ	L
HY-100	SMOOTH	SALT WATER	2980	0.00052	0.00976	27500	132000	5.000	SQ	L
HY-100	SMOOTH	SALT WATER	3120	0.00070	0.00935	23750	114000	0.075	SQ	L
HY-100	SMOOTH	SALT WATER	3777	0.00062	0.00840	24500	117600	0.100	SQ	L
HY-100	SMOOTH	SALT WATER	4555	0.00015	0.00765	22400	107500	0.020	SQ	L
HY-100	SMOOTH	SALT WATER	4999	0.00030	0.00820	25000	120000	1.200	SQ	L
HY-100	SMOOTH	SALT WATER	5855	0.00012	0.00740	22000	105600	0.500	SQ	L
HY-100	SMOOTH	SALT WATER	6491	0.00011	0.00712	20500	98400	0.075	SQ	L
HY-100	SMOOTH	SALT WATER	8630	0.00010	0.00715	21800	104600	0.300	SQ	L
HY-100	SMOOTH	SALT WATER	10029	0.00008	0.00710	20000	96000	1.667	SQ	L
HY-100	SMOOTH	SALT WATER	10414	0.00011	0.00700	21250	102000	1.200	SQ	L
HY-100	SMOOTH	SALT WATER	15746	0.00010	0.00670	19800	95000	5.000	SQ	L
HY-100	V-NOTCH	AIR	172	0.00900	0.02100	33000	158700	1.000	SAW	T
HY-100	V-NOTCH	AIR	195	0.00706	0.01960	34350	165900	1.000	SAW	L
HY-100	V-NOTCH	AIR	330	0.00620	0.01836	31650	152200	1.000	SAW	T
HY-100	V-NOTCH	AIR	352	0.00640	0.01960	35000	168500	1.000	SAW	L
HY-100	V-NOTCH	AIR	430	0.00500	0.01700	31700	152400	1.000	SAW	L
HY-100	V-NOTCH	AIR	631	0.00164	0.01326	29900	143800	1.000	SAW	L
HY-100	V-NOTCH	AIR	656	0.00280	0.01436	31700	152400	1.000	SAW	L
HY-100	V-NOTCH	AIR	757	0.00240	0.01340	29500	141800	1.000	SAW	T
HY-100	V-NOTCH	AIR	807	0.00238	0.01350	31150	149800	1.000	SAW	T
HY-100	V-NOTCH	AIR	1020	0.00140	0.01160	28500	137000	1.000	SAW	L
HY-100	V-NOTCH	AIR	1046	0.00226	0.01316	30650	147400	1.000	SAW	L
HY-100	V-NOTCH	AIR	1155	0.00192	0.01202	29200	140400	1.000	SAW	L
HY-100	V-NOTCH	AIR	1212	0.00152	0.01144	28750	138200	1.000	SAW	T

IRON BASE ALLOYS

MATERIAL	TYPE OF SPECIMEN	TEST ENVIRONMENT	CYCLES TO FAILURE N	EP IN/IN	ET IN/IN	NT IN-LB	SR PSI	CYCLES PER MINUTE	CYCLE PATTERN	SPECIMEN DIRECTION
HY-100	V-NOTCH	AIR	1487	0.00100	0.01040	26750	128600	1.000	SAW	T
HY-100	V-NOTCH	AIR	1689	0.00234	0.01360	30650	147400	1.000	SAW	L
HY-100	V-NOTCH	AIR	1827	0.00060	0.01010	27150	130500	1.000	SAW	T
HY-100	V-NOTCH	AIR	2566	0.00030	0.00980	26500	127500	1.000	SAW	L
HY-100	WELDED 11018	AIR	694	0.00450	0.01710	33000	158000	1.000	SAW	L
HY-100	WELDED 11018	AIR	1085	0.00264	0.01410	31000	149000	1.000	SAW	L
HY-100	WELDED 11018	AIR	2825	0.00120	0.01120	28250	136000	1.000	SAW	L
HY-100	WELDED 11018	AIR	4556	0.00090	0.01040	26000	125000	1.000	SAW	L
HY-100	WELDED 9018	AIR	1108	0.00424	0.01460	30850	148300	1.000	SAW	L
HY-100	WELDED 9018	AIR	2251	0.00280	0.01296	27950	134400	1.000	SAW	L
HY-100	WELDED 9018	AIR	6671	0.00070	0.00880	23000	110600	1.000	SAW	L
HY-100	WELDED 9018	AIR	7805	0.00070	0.00902	23750	114200	1.000	SAW	L
HY-100	WELDED B-88-A632	AIR	1495	0.00220	0.01316	29950	140000	1.000	SAW	L
HY-100	WELDED B-88-A632	AIR	1507	0.00234	0.01282	30400	146200	1.000	SAW	L
HY-100	WELDED B-88-A632	AIR	2602	0.00116	0.01016	25500	122600	1.000	SAW	L
HY-100	WELDED B-88-A632	AIR	8129	0.00060	0.00874	23000	110600	1.000	SAW	L
HY-150	SMOOTH	AIR	1401	0.00180	0.01530	42100	202100	1.000	SAW	L
HY-150	SMOOTH	AIR	7378	0.00015	0.00980	31000	148800	1.000	SAW	L
HY-150	SMOOTH	AIR	18059	0.00008	0.00855	27850	133700	1.000	SAW	L
HY-150	SMOOTH	AIR	447	0.00250	0.01940	45400	217900	5.000	SQ	L
HY-150	SMOOTH	AIR	1220	0.00190	0.01590	41400	198700	5.000	SQ	L
HY-150	SMOOTH	AIR	4093	0.00016	0.01180	34500	165600	5.000	SQ	L
HY-150	SMOOTH	AIR	5843	0.00020	0.01095	32000	153600	5.000	SQ	L
HY-150	SMOOTH	AIR	15314	0.00016	0.00850	28000	134400	5.000	SQ	L
HY-150	V-NOTCH	AIR	886	0.00114	0.01408	38200	183600	1.000	SAW	L
HY-150	V-NOTCH	AIR	5272	<0.00001	0.00935	28250	135600	1.000	SAW	L
HY-150	V-NOTCH	AIR	11397	<0.00001	0.00750	22400	107500	1.000	SAW	L
HY-230	SMOOTH	AIR	12	0.00040	0.01992	52700	253400	1.000	SAW	L
HY-230	SMOOTH	AIR	3390	<0.00001	0.01690	42350	203600	1.000	SAW	L
HY-230	SMOOTH	AIR	8624	<0.00001	0.01290	35100	168600	1.000	SAW	L
HY-230	V-NOTCH	AIR	700	<0.00001	0.01342	44600	214500	1.000	SAW	L

ALUMINUM BASE ALLOYS

MATERIAL	TYPE OF SPECIMEN	TEST ENVIRONMENT	CYCLES TO FAILURE N	EP IN/IN	ET IN/IN	MT IN-LB	SR PSI	CYCLES PER MINUTE	CYCLE PATTERN	SPECIMEN DIRECTION
5086-H112	SMOOTH	AIR	707	0.00660	0.01744	11250	54100	1.000	SAW	L
5086-H112	SMOOTH	AIR	1299	0.00446	0.01492	10613	51000	1.000	SAW	L
5086-H112	SMOOTH	AIR	1932	0.00284	0.01332	10480	50400	1.000	SAW	L
5086-H112	SMOOTH	AIR	4449	0.00090	0.00994	9280	44500	1.000	SAW	L
5086-H112	SMOOTH	AIR	4826	0.00180	0.01060	8890	43200	1.000	SAW	L
5086-H112	SMOOTH	AIR	30858	0.00040	0.00730	7000	33600	1.000	SAW	L
5086-H112	V-NOTCH	AIR	109	0.00570	0.01620	12410	59600	1.000	SAW	L
5086-H112	V-NOTCH	AIR	2871	0.00066	0.00730	8440	40600	1.000	SAW	L
5086-H32	SMOOTH	AIR	508	0.00780	0.01912	11800	56600	1.000	SAW	L
5086-H32	SMOOTH	AIR	1082	0.00560	0.01620	10880	52200	1.000	SAW	L
5086-H32	SMOOTH	AIR	2112	0.00280	0.01228	10925	52400	1.000	SAW	L
5086-H32	SMOOTH	AIR	12217	0.00070	0.00794	8300	39800	1.000	SAW	L
5086-H32	V-NOTCH	AIR	600	0.00276	0.01220	10100	48500	1.000	SAW	L
5086-H32	V-NOTCH	AIR	2683	0.00160	0.00990	9000	43200	1.000	SAW	L
5086-H32	V-NOTCH	AIR	4693	0.00038	0.00715	7200	34600	1.000	SAW	L
5086-H32	V-NOTCH	AIR	12163	0.	0.00616	6080	29200	1.000	SAW	L
5456-H311	SMOOTH	AIR	620	0.00516	0.01730	12500	60100	1.000	SAW	L
5456-H311	SMOOTH	AIR	1783	0.00290	0.01316	10940	52600	1.000	SAW	L
5456-H311	SMOOTH	AIR	7535	0.00134	0.01040	9370	45000	1.000	SAW	L
5456-H311	SMOOTH	AIR	27856	0.00028	0.00740	7300	35100	1.000	SAW	L
5456-H311	V-NOTCH	AIR	127	0.00538	0.01764	12700	61000	1.000	SAW	L
5456-H311	V-NOTCH	AIR	723	0.00144	0.01080	9560	46000	1.000	SAW	L
5456-H311	V-NOTCH	AIR	3340	0.00022	0.00708	7038	33800	1.000	SAW	L
5456-H321	SMOOTH	AIR	622	0.01074	0.02260	12000	57600	1.000	SAW	L
5456-H321	SMOOTH	AIR	1159	0.00764	0.01820	11880	57000	1.000	SAW	L
5456-H321	SMOOTH	AIR	3300	0.00352	0.01230	10340	49600	1.000	SAW	L
5456-H321	SMOOTH	AIR	16618	0.00144	0.00876	8760	37600	1.000	SAW	L
5456-H321	V-NOTCH	AIR	521	0.00560	0.01580	10800	51800	1.000	SAW	L
5456-H321	V-NOTCH	AIR	1096	0.00396	0.01328	9800	47000	1.000	SAW	L
5456-H321	V-NOTCH	AIR	4251	0.00140	0.00880	7000	37400	1.000	SAW	L
5456-H321	V-NOTCH	AIR	5273	0.00087	0.00770	7200	34600	1.000	SAW	L
6061-T6	SMOOTH	AIR	1059	0.00450	0.01866	13620	65400	1.000	SAW	L
6061-T6	SMOOTH	AIR	2037	0.00020	0.01028	10200	49100	1.000	SAW	L
6061-T6	SMOOTH	AIR	4404	0.00028	0.01000	10150	48800	1.000	SAW	L
6061-T6	SMOOTH	AIR	7931	0.00012	0.00912	9120	46100	1.000	SAW	L
6061-T6	V-NOTCH	AIR	402	0.00460	0.01628	14100	67800	1.000	SAW	L
6061-T6	V-NOTCH	AIR	887	0.00008	0.00870	8910	42800	1.000	SAW	L
6061-T6	V-NOTCH	AIR	[illegible]24	0.00070	0.00660	7800	37500	1.000	SAW	L

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ALUMINUM BASE ALLOYS

MATERIAL	TYPE OF SPECIMEN	TEST ENVIRONMENT	CYCLES TO FAILURE N	EP IN/IN	ET IN/IN	MT IN-LB	SR PSI	CYCLES PER MINUTE	CYCLE PATTERN	SPECIMEN DIRECTION
6061-T6	V-NOTCH	AIR	2365	0.00110	0.01126	10950	52600	1.000	SAW	L
7079-T6	SMOOTH	AIR	620	0.00220	0.01960	18150	87100	1.000	SAW	L
7079-T6	SMOOTH	AIR	1066	0.00046	0.01560	14700	70600	1.000	SAW	L
7079-T6	SMOOTH	AIR	8560	0.00000	0.00968	10880	52200	1.000	SAW	L
7079-T6	SMOOTH	AIR	18963	0.00000	0.00820	9024	43300	1.000	SAW	L
7079-T6	V-NOTCH	AIR	375	0.00090	0.01650	16300	80600	1.000	SAW	L
7079-T6	V-NOTCH	AIR	1110	0.00020	0.01440	15000	72000	1.000	SAW	L
7079-T6	V-NOTCH	AIR	3734	0.00000	0.01060	11300	55200	1.000	SAW	L
7079-T6	V-NOTCH	AIR	9533	0.00000	0.00772	8500	40800	1.000	SAW	L

NICKEL BASE ALLOYS

MATERIAL	TYPE OF SPECIMEN	TEST ENVIRONMENT	CYCLES TO FAILURE N	EP IN/IN	ET IN/IN	MT IN-LB	SA PSI	CYCLES PER MINUTE	CYCLE PATTERN	SPECIMEN DIRECTION
MONEL	SMOOTH	AIR	954	0.00940	0.01600	19500	93600	1.000	SAW	T
MONEL	SMOOTH	AIR	1514	0.00680	0.01440	19500	93600	1.000	SAW	T
MONEL	SMOOTH	AIR	4725	0.00260	0.00910	16400	78700	1.000	SAW	T
MONEL	SMOOTH	AIR	16388	0.00100	0.00650	14500	69600	1.000	SAW	T
MONEL	V-NOTCH	AIR	1203	0.00540	0.01260	18250	87600	1.000	SAW	L
MONEL	V-NOTCH	AIR	12681	0.00500	0.00520	12750	61200	1.000	SAW	L
K-MONEL	SMOOTH	AIR	681	0.00590	0.02210	45000	216000	1.000	SAW	L
K-MONEL	SMOOTH	AIR	1680	0.00260	0.01560	39100	188000	1.000	SAW	L
K-MONEL	SMOOTH	AIR	3969	0.00050	0.01310	34100	164000	1.000	SAW	L
K-MONEL	SMOOTH	AIR	5217	0.00010	0.01340	30000	144000	1.000	SAW	L
K-MONEL	V-NOTCH	AIR	1110	0.00140	0.01490	35800	171800	1.000	SAW	L
K-MONEL	V-NOTCH	AIR	6774	0.00002	0.00900	24750	118800	1.000	SAW	L
INCONEL	SMOOTH	AIR	609	0.01540	0.02250	18200	87360	1.000	SAW	L
INCONEL	SMOOTH	AIR	1709	0.01080	0.01680	16250	78000	1.000	SAW	L
INCONEL	SMOOTH	AIR	6728	0.00560	0.01050	14000	67200	1.000	SAW	L
INCONEL	SMOOTH	AIR	21664	0.00360	0.00780	11500	55200	1.000	SAW	L
INCONEL	V-NOTCH	AIR	614	0.01120	0.01690	15600	74900	1.000	SAW	L
INCONEL	V-NOTCH	AIR	5613	0.00340	0.00750	12000	57600	1.000	SAW	L
INCONEL 718	SMOOTH	AIR	598	0.00390	0.01900	44000	211200	1.000	SAW	L
INCONEL 718	SMOOTH	AIR	1115	0.00160	0.01630	44800	215000	1.000	SAW	L
INCONEL 718	SMOOTH	AIR	5205	0.00020	0.01160	36000	172800	1.000	SAW	L
INCONEL 718	SMOOTH	AIR	9095	0.00010	0.01040	32000	153000	1.000	SAW	L
INCONEL 718	V-NOTCH	AIR	868	0.00110	0.01470	41500	199200	1.000	SAW	L
INCONEL 718	V-NOTCH	AIR	4774	0.00000	0.00980	30000	144000	1.000	SAW	L
NIONEL	SMOOTH	AIR	837	0.01030	0.01830	20700	99400	1.000	SAW	L
NIONEL	SMOOTH	AIR	1732	0.00720	0.01470	20630	99000	1.000	SAW	L
NIONEL	SMOOTH	AIR	4076	0.00560	0.01260	18100	86900	1.000	SAW	L
NIONEL	SMOOTH	AIR	9899	0.00300	0.00890	17100	82100	1.000	SAW	L
NIONEL	V-NOTCH	AIR	1222	0.00640	0.01350	18000	86400	1.000	SAW	L
NIONEL	V-NOTCH	AIR	6762	0.00180	0.00680	14080	67600	1.000	SAW	L

COPPER BASE ALLOYS

MATERIAL	TYPE OF SPECIMEN	TEST ENVIRONMENT	CYCLES TO FAILURE N	EP IN/IN	ET IN/IN	MT IN-LB	SR PSI	CYCLES PER MINUTE	CYCLE PATTERN	SPECIMEN DIRECTION
70-30 CU-NI	SMOOTH	AIR	1812	0.01006	0.01580	10850	52100	5.000	SQ	T
70-30 CU-NI	SMOOTH	AIR	7361	0.00517	0.00957	8700	41800	5.000	SQ	T
70-30 CU-NI	SMOOTH	AIR	27691	0.00225	0.00582	7400	35500	5.000	SQ	T
70-30 CU-NI	SMOOTH	SALT WATER	14095	0.00180	0.00570	8400	40300	0.100	SQ	T
70-30 CU-NI	SMOOTH	SALT WATER	21330	0.00235	0.00588	7400	35400	0.250	SQ	T
70-30 CU-NI	SMOOTH	SALT WATER	30098	0.00220	0.00590	7000	33600	0.600	SQ	T
GUN METAL	SMOOTH	AIR	632	0.00932	0.01480	7800	37400	5.000	SQ	CAST
GUN METAL	SMOOTH	AIR	1908	0.00664	0.01130	6750	32400	5.000	SQ	CAST
GUN METAL	SMOOTH	AIR	13364	0.00095	0.00450	4800	23000	5.000	SQ	CAST
GUN METAL	SMOOTH	SALT WATER	3448	0.00137	0.00495	5350	25700	0.600	SQ	CAST
GUN METAL	SMOOTH	SALT WATER	15925	0.00147	0.00481	4750	22800	0.250	SQ	CAST
GUN METAL	SMOOTH	SALT WATER	33145+	0.00015	0.00315	4300	19800	0.100	SQ	CAST
GUN METAL	SMOOTH	SALT WATER	50360	0.00055	0.00387	4000	19200	5.000	SQ	CAST
SUPERSTON-40	SMOOTH	AIR	2253	0.00440	0.01392	15700	75400	5.000	SQ	CAST
SUPERSTON-40	SMOOTH	AIR	7450	0.00274	0.01086	12250	58900	5.000	SQ	CAST
SUPERSTON-40	SMOOTH	AIR	26941	0.00127	0.00820	11350	54500	5.000	SQ	CAST
SUPERSTON-40	SMOOTH	AIR	61526	0.00010	0.00580	9750	46800	5.000	SQ	CAST
SUPERSTON-40	SMOOTH	SALT WATER	5806	0.00124	0.00802	11600	55700	0.250	SQ	CAST
SUPERSTON-40	SMOOTH	SALT WATER	9603	0.00111	0.00790	12000	57600	0.100	SQ	CAST
SUPERSTON-40	SMOOTH	SALT WATER	14693	0.00097	0.00732	11000	52800	0.600	SQ	CAST

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1. Submarines - Construction
2. Steel - Fatigue
3. Alloys - Fatigue
4. Metals - Fatigue

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