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INVESTIGATION OF THE STATISTICAL NATURE OF THE FATIGUE OF METALS

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SUMMARY

It has been widely accepted recently that statistical methods of investigation are necessary for meaningful work in studies on the fatigue of metals. The statistical nature of the endurance limit was first demonstrated in the Metals Research Laboratory, Carnegie Institute of Technology, less than 5 years ago. A subsequent study showed that for steel the chief metallurgical variable influencing the statistical nature was the nonmetallic inclusion count.

The present investigation utilized the statistical methods developed in previous research to study the scatter found in aluminum alloys and the effect of the morphology of the carbide phase on the scatter in a eutectoid steel. The scatter in fatigue life for 24S and 75S aluminum was found to be comparable with that reported previously for steel. As was found in previous investigations, the scatter increased with decreasing stress level. A pronounced effect of microstructure was found when a coarse pearlitic structure was compared with a coarse spheroidized structure in the same steel with the same tensile strength. The scatter from the pearlitic structure was significantly less than that in the spheroidized, this result being attributed to the stress concentration produced by the sharp carbide lamellae.

INTRODUCTION

At Carnegie Institute of Technology, under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics, a special program was designed to study the statistical nature of the fatigue of metals. The first phase of this program, the results of which were reported in NACA TN 2719, was concerned principally with laying the foundation for statistical investigations of fatigue and determining the metallurgical variables which were of importance in producing the statistical variation. The fatigue behavior of several ferrous materials was studied and statistical methods were used to analyze the data. The results obtained indicated that fatigue data are amenable to statistical analysis and that statistical methods allow a more precise description of fatigue behavior and evaluation of the merit of particular data. It was shown that for steel the chief metallurgical variable influencing the statistical nature was the nonmetallic inclusion content.

The investigation was then continued with the purpose of evaluating the effect of microstructure (carbide morphology) on fatigue scatter in a eutectoid steel and studying the statistical variation in commercial aluminum alloys. The present report contains the results of this phase of the experimental work. The statistical methods developed previously were utilized in the present investigation which included a study of the fatigue properties and their statistical variation of a eutectoid steel heat-treated to pearlitic and spheroidized structures of the same tensile strength and of the statistical variation of fatigue properties of commercially pure aluminum (2S) and 24S aluminum alloy heat-treated to two different structures.

LITERATURE REVIEW

Previous investigations in the Metals Research Laboratory, Carnegie Institute of Technology, have established the fact that both the fatigue life and endurance limit are subject to marked variability and therefore must be studied statistically. Ransom and Mehl (ref. 1) first showed the statistical nature of the endurance limit and Epremian and Mehl (ref. 2) systematically studied the effect of metallurgical variables on both the endurance limit and the fracture range of the S-N curve. They found that for the steels studied the chief metallurgical variable influencing the statistical nature was the inclusion content of the steel. However, it was found that for a given heat of SAE 4340 steel (i.e., at a given composition and inclusion rating) the variability of the endurance limit was markedly affected by the microstructure. No significant difference was obtained between the fatigue lives in the fracture curve. A quenched and tempered structure yielded greater dispersion in the endurance limit than a quenched and spheroidized structure. However, since the two structures were at different tensile strength levels (168,000 psi and 103,000 psi), no directly comparable conclusions could be drawn concerning the effect of the variable of metallurgical structure.

Moreover, it was felt that the effect of the morphology of the cementite phase on the fatigue properties should be definitely established, this time with both structures at the same strength level and with two structures of well-defined carbide distributions. Gensamer and coworkers in this laboratory (ref. 3) have shown that the tensile properties depend primarily upon the mean free ferrite path irrespective of the shape of the cementite particles. In fatigue, however, it might be expected that the endurance limit would depend upon the shape of the second phase as well as its distribution. In keeping with current theories of fracture it might well be proposed that fatigue failure in a steel with a ferrite-cementite structure initiates by fracture of a brittle cementite platelet or by formation of a crack at the cementite-ferrite interface. From the differences in the geometry of the particles it would seem that cementite lamellae should fracture more easily than spheroids. Thus, in fatigue, where the ductility of the metal has less opportunity to exert its influence in dissipating stress concentrations than under static loads, it might be expected that lamellar pearlite would have lower fatigue properties than a spheroidal structure with equivalent mean free ferrite path.

Recent work by Grant (ref. 4) with fatigue tests on flake and nodular cast iron has borne this out for those materials. Tests on flake and nodular irons of comparable tensile strengths showed that the latter had higher endurance limits. In the notched or grooved condition there was no advantage for the nodular structure. Grant made no study of the statistics of fatigue.

Only very limited information on the statistics of the fatigue properties of aluminum and its alloys exists in the literature. Ravilly (ref. 5) conducted torsional fatigue tests on 200 annealed aluminum specimens and found that the scatter was somewhat less than that for similar specimens of annealed steel and Armco iron. Yen and Dolan (ref. 6) in investigating the effect of short time rests and anneals on 75S-T6 alloy tested a sufficient number of specimens to make a statistical analysis of their data. Recently, additional data on the fatigue statistics of this alloy have been published by Dolan and Brown (ref. 7) for new stress levels. The mechanical properties of the material are identical in both reports, the only difference being an increase in the diameter of the test specimen from 0.140 inch to 0.150 inch in the latter work. Logarithmic mean life $\overline{\log N}$ and the standard deviation σ have been calculated from each of these sources and are presented in table V and figure 5. Their results will be discussed in conjunction with the data obtained in this investigation in a later section of this report.

An interesting theory recently proposed by Lunchick (ref. 8) may throw additional light on the reasons for scatter in fatigue life. In this theory the individual grain of the material is considered to be the basic structural element in which fatigue failure occurs. Bragg's hypothesis, that the elastic strength of a grain varies inversely with the mean free path for slip, is basic to this theory. Thus, it is proposed that microscopic cracks result from slip within those grains which are larger than some critical grain size for the particular stress level. Using experimental evidence that the grain-size distribution of annealed aluminum is normal for log N, a mathematical correlation is made between the strength of the metal and the structure. Considering the finite fatigue life to be controlled by the number of microscopic cracks initiated and the rate of propagation of these cracks, it is shown that the fatigue life is increased by (a) decreasing the mean grain size, (b) making the material more uniform in grain-size distribution, and (c) decreasing the volume of material subjected to stresses above a given reference stress.

The scatter in fatigue life at constant stress level is explained by a variation in the number of microscopic cracks initiated at a given stress. This latter quantity is believed to depend on the grain-size distribution over the planes of failure. Thus, according to this theory the scatter in fatigue life for geometrically similar specimens is due primarily to changes in the structure of the material on the plane of failure which may be expressed in terms of changes of mean grain size or standard deviation of the grain-size distribution. It would follow that the specimens with longer life, $\overline{\log N} + 2\sigma$, would be the ones with finer grain size and/or more uniform distribution of grain size.

Lunchick presented little experimental evidence in support of this theory. No consideration was made of such factors as grain orientations and grain-boundary constriction. Information on grain-size distribution and rate of crack propagation is scanty and often unreliable. Further, Bragg's hypothesis upon which the theory is based can only be considered a broad generalization and not an exact law of nature. The theory as proposed is valid only for single-phase alloys, such as annealed aluminum, although presumably, by substituting mean free path for slip in place of grain size, it could be qualitatively extended to the case of some age-hardened aluminum alloys and ferrite-cementite aggregates in steel. This is not to be considered a conclusive theory but one which may serve as a springboard for future investigations. It is possible that the basic philosophy in this approach can be tested by work on single crystals.

EXPERIMENTAL WORK

Test Specimens

A plain carbon eutectoid steel of the following chemical composition was used for the first phase of this investigation:

C	Si	Mn	S	P	Cr
0.78	0.22	0.27	0.016	0.011	0.05

The steel was received as 5/8-inch-diameter rounds, cut into fatigue blanks, and heat-treated by the procedures described below. R. R. Moore rotating-beam fatigue specimens of 0.300-inch diameter with a $5\frac{1}{4}$-inch radius were machined from these blanks. The specimens were rough-machined in four cuts, using a fine cut for the last pass. They were then ground to within 0.001 inch of the final dimensions and then polished with Nos. 180, 400, and 600 abrasive tape, using alternate passes at 45° and parallel with the axis. The final polish was such that the fine scratches ran in the longitudinal direction.

The aluminum specimens were prepared from material of the following composition:

	Cu	Fe	Si	Mn	Mg	Ti	Al
2S	0.11	0.60	0.13	0.005	0.005	0.01	Bal.
24S	3.95	.20	.09	.59	1.44	.03	Bal.

These were commercial materials obtained through the courtesy of the Aluminum Company of America. Cantilever fatigue specimens of rectangular cross section of the same type and dimensions as those used by Epremian and Mehl (ref. 2) were machined from the as-received material. The dimensions at the maximum stress section near the fillet were 0.300 by 0.500 inch. Residual stresses imposed by the milling operation were removed by heat-treating after machining. The specimens were then carefully hand-polished on Nos. 1, 1/0, 2/0, and 3/0 metallographic polishing papers, using a liberal amount of paraffin dissolved in kerosene as a lubricant. The specimens were polished in the longitudinal direction so that the fine scratches were parallel to the direction of the principal fiber stresses.

After polishing, the critical area was covered with electrical scotch tape and masking tape and the grip portion of the specimen which is clamped in the holder of the fatigue machine was lightly shot-peened. This was necessary to prevent premature failure in the clamped portion of the specimen due to fret-corrosion fatigue. The same difficulty was experienced by Epremian and Mehl with steel specimens. It may now be concluded that this is a necessary precaution to be taken with all specimens tested in this type of vibrating-cantilever fatigue machine.

Test Equipment and Procedure

The eutectoid steel specimens were tested on four R. R. Moore rotating-beam machines at speeds between 8,000 and 10,000 rpm. The weights were accurately calibrated and the effective dead weight was determined for each machine. The weights were applied with the machine at rest and the machine was then brought up to speed. The machines were equipped with a setscrew device which actuated a relay when a small deflection of the specimen occurred. Thus the specimens were not run to complete failure but to the point where a crack formed, varying in size from that not visible without a microscope to about one quarter through the diameter. Tests showed that there was no significant difference between this criterion for failure and complete fracture. With fractures of this type it was hoped to obtain better microscopic correlation between the actual failure and the metallurgical structure. The minimum diameter of the specimens was measured optically on a comparator to 0.0001 inch. All specimens were examined microscopically at 100 diameters before testing for circumferential scratches and other surface defects. The criterion for a nonfailure in the endurance range was taken as 2.5×10^7 cycles, although several specimens were run to 5×10^7 cycles to see if there was any tendency for delayed failure.

The applied stress was calculated by the formula

$$S = \frac{Mc}{I} = \frac{16PL}{\pi D^3}$$

where

S	applied stress, psi
M	bending moment, in-lb
c	distance from outermost fiber to neutral axis, in.
I	moment of inertia, $in.^4$
P	total applied load, lb
L	lever arm, in.
D	diameter of specimen, in.

The average percentage error in stress was about ±0.7 percent.

The fatigue tests on the aluminum alloys were conducted in six General Electric Company pneumatic vibrating-cantilever machines which were previously described by Quinlan (ref. 9) and Epremian and Mehl (ref. 2). This machine pneumatically vibrates a cantilever specimen at its natural frequency of vibration. The criterion for failure is the formation of the first small crack, corresponding to a drop in the natural frequency of the specimen of about 2 percent.

The stress applied to these specimens was calculated by the equation (see ref. 2 for derivation)

$$S = KA_m f^2$$

where K is a constant determined by the dimensions of the specimen and its experimentally determined deflection curve, A_m is the semi-amplitude of vibration at the free end of the specimen in inches, and f is the natural frequency of vibration in cycles per second. The stress equations obtained were:

$$\text{24S-O:} \quad S = 18.35 A_m f^2$$

$$\text{24S-T4:} \quad S = 18.40 A_m f^2$$

$$\text{2S:} \quad S = 16.56 A_m f^2$$

The average percentage errors in stress for 24S-T4, 24S-O, and 2S specimens were ±2.5 percent, ±3.25 percent, and ±4.0 percent, respectively. This is due to the fact that the percentage error is a function of the maximum amplitude of vibration, which was considerably lower for the 24S-O and 2S specimens.

Heat Treatments and Mechanical Properties

Considerable effort was spent in developing a heat treatment for the eutectoid steel which would produce the structures desired (i.e., coarse pearlite and coarse spheroidite) with the same tensile strength for each structure. Since a large number of specimens were involved, about 200 for each structure, and uniformity of structure and properties was essential, it was necessary to have the heat treatment made in large batches by a commercial firm. The small difference in tensile strengths between the two structures resulted from the difficulties in correlating large-scale commercial heat treatments with laboratory results.

The spheroidized fatigue blanks were austenitized at 845° C for 1 hour and quenched in oil to produce a martensite-fine pearlite structure amenable for spheroidizing. The blanks were then spheroidized in a high-temperature salt pot at 685° C for 15 hours and water-quenched.

The pearlitic specimens were austenitized at 845° C for 1 hour and then transferred rapidly to a salt pot at 705° C and isothermally reacted for 20 hours. They were then air-cooled to room temperature.

Fatigue specimens were machined from the heat-treated blanks in the manner described in the previous section. The polished fatigue specimens were then stress-relieved for 1 hour at 593° C (1,100° F) in a vacuum furnace. No evidence of oxide formation or other surface reaction resulted from this treatment.

The resulting mechanical properties of the two structures are given in table I. The results are the average of 10 tensile tests for each structure.

The aluminum-alloy specimens were heat-treated after machining. This was possible because of the simple shape of the fatigue specimens and the relatively low temperatures used. The natural aged temper (24S-T4) was produced by solution-heating at 490° C for 2 hours and quenching in water. No distortion was produced by this treatment. The specimens were then aged at room temperature to a stabilized condition (i.e., one in which no change in hardness was found after 2 weeks of aging). They were then carefully hand-polished, shot-peened, and tested.

The annealed specimens (24S-O) were produced by heating at 420° C for 8 hours and then slowly cooling overnight in the furnace. This resulted in a very fine precipitate uniformly distributed throughout the alloy.

The 2S specimens were machined and polished, as outlined above, and then given a stress relief for 2 hours at 200° C. This did not produce a fully annealed condition, as would have been desired, but rather produced the softest structure which could be tested in the pneumatic machines without excessive work-hardening producing changes in the deflection amplitude during the progress of the test. The structure consisted of the grains elongated in the longitudinal direction of the specimen. The mechanical properties resulting from these heat treatments are given in table II.

EXPERIMENTAL RESULTS AND ANALYSIS

Eutectoid Steel

The fatigue statistics for the eutectoid steel are presented in table III and the S-N curves plotted in figures 1, 2, and 3. The statistical methods used were outlined by Epremian and Mehl (ref. 2). Twenty specimens were tested at each stress and the logarithmic mean life, mean life (antilogarithm of $\overline{\log N}$), standard deviation, standard estimate of error, and relative standard deviation were determined.

The statistics of the endurance limit were obtained by the probit method as described by Finney (ref. 10) and Epremian and Mehl. Briefly, probit analysis is a statistical method for treating a "go - no-go" type of distribution, such as is encountered within the endurance range. Here, it is not the number of cycles which a specimen undergoes which is of importance, but the criterion is whether a specimen fails or runs out. If the distribution of percent failure with stress is normal, a straight line will be obtained when they are plotted on probability graph paper. If the percentage of failures are converted to probits, using the tables available in Finney's book, and the probit of percentage of failures is plotted against stress on Cartesian coordinates, the characteristic probit plot is obtained. The best straight line through the points has the following equation:

$$Y = 5 + \frac{1}{\sigma} (S - \bar{S})$$

where

σ standard deviation of endurance limit, psi

$\bar{S}$ mean endurance limit, psi

S level of stress, psi

Y probit of percentage of failures corresponding to stress S

5 probit of 50 percent of failures

It should be evident from the above equation that the mean endurance limit $\bar{S}$ is the stress at which 50 percent failures and 50 percent run-outs are obtained. Also, the slope of the probit line is the reciprocal of the standard deviation of the mean endurance limit. In applying the probit method, a provisional curve is drawn through the points and then corrected by an analytical method of successive approximations until the best fit is obtained. The χ^2 test for goodness of fit is then applied to the final probit regression line to see if it satisfies the criterion of a normal distribution.

Figure 1 shows the S-N curve for the spheroidized eutectoid steel. It will be noted that the fracture curve (finite life portion) has the sigmoid shape observed by Epremian and Mehl (ref. 2) for all of their steels and structures. Unfortunately, the range of stress which could be studied was limited by severe heating of the specimen at stresses above 47,500 psi. The generation of heat within the specimen was pronounced even when the fatigue machines were operated at a slow speed of 4,500 rpm and is evidence of elastic hysteresis within the material. It should be noted that the stress at which this heating became pronounced, 50,000 psi, is well below the static yield point of the steel, 71,000 psi.

Figure 2 shows the fatigue statistics for the pearlitic eutectoid steel. It will be noted that the scatter in fatigue life, as denoted by the $\pm 2\sigma$ limits, is much smaller than that for the previous curve (fig. 1). Also, this curve does not have a sigmoid shape. No explanation is offered for the differences in the shapes of these curves. However, it should be noted that, out of the six different ferrous materials studied statistically in this laboratory, this is the first instance where a sigmoid curve was not obtained.

The F test (ref. 11) for the comparison of the variabilities of two sets of measurements was applied to the standard deviations for each structure at a series of stresses to see if the scatter changed significantly with stress level. Briefly, the F test consists of taking the ratio of the square of the standard deviations of two sets of measurements. If the value of this ratio is greater than the value given in tables of the F distribution for the particular confidence limit and degrees of freedom, then the two standard deviations differ significantly. It was found that for both the spheroidized and pearlitic structures the scatter in fatigue life increased significantly with decrease in stress level. It should be noted for the spheroidized structure that only the stress of 47,500 psi was outside of the statistical range of the endurance limit. Thus, at lower stresses the statistics of finite life are based only on the number of specimens out of the 20 tested at that stress which failed. The statistics at the stresses where less than 85 percent of the specimens failed are thus not so reliable as the other data but are included only to indicate the trend as the stress level is decreased.

One criticism of the statistical methods used in treating fatigue data has been that actually two different distributions are considered, a distribution of $\log N$ against stress in the finite-life region and a distribution of stress against percentage failure in the endurance range. Actually, it is only at the small range of stress near the 2σ limit of the mean endurance limit where this produces difficulty. At these stresses there is no chance of including run-outs in the fracture statistics. Actually, the split between fracture-curve statistics and endurance-limit statistics is not quite so arbitrary as it would appear at first glance. It certainly does make sense from the design standpoint. The first question that a designer would ask is, at a given stress, will the part break or run out? For his answer, he has only to look at the endurance-limit statistics to find the probability of a run-out. If the probability for a run-out is small, his next question is, at what number of cycles will it break? The answer to this question is found from the finite-life statistics.

The differences in fatigue properties due to the morphology of the cementite phase are evident from figure 3. Although both structures had almost identical tensile strengths, the mean endurance limit of the pearlitic structure is much lower than that of the spheroidized structure. Also, the scatter for the pearlite in both the fracture range and endurance limit is seen to be less.

The variability in fatigue life of the two structures was compared at equal percentage stress above their mean endurance limits, so as to take into consideration the change of scatter with stress level, using the F test. The pearlitic structure was found to have significantly smaller scatter statistically.

The differences in the variability of the endurance limits of the two structures were tested by the method developed by Epremian and Mehl (ref. 2). This method utilizes the t test in determining the significance of differences in variability of the slope of the probit line. No significant difference between the two structures was found. This is surprising in view of the fact that Epremian and Mehl found that the variability of the endurance limit was more sensitive to changes in structure than the variability in finite life. It will be recalled from the brief discussion of probit analysis that a requirement of this method is that the final probit line satisfies the χ^2 test for a normal distribution. When the χ^2 test was applied to the probit line for the spheroidized structure, a probability of $P = 0.50$ was obtained. This means that there is a 50-percent probability that a fit to a normal distribution as bad as or worse than that obtained might occur because of chance variations of sampling. Statisticians generally regard a value of $P < 0.05$ as indicating a poor fit.

The probit line of the data for the pearlitic structure listed in table III did not meet the χ^2 test. The probability obtained was $P \approx 0.01$. In analyzing the data, it is seen that 90-percent failures were obtained at both 36,000 and 35,000 psi. Also, it is seen that the two lowest stresses produced values at the lower end of the distribution. There are three possible explanations for this result. The distribution of percentage of failures with stress level may not be normal for this case, some unrecognizable experimental differences may have been present at 36,000 psi, or the distribution is normal but represents the improbable but nevertheless possible result which would be obtained about 1 time out of every 100 determinations. The fact that an unfortunate selection of stresses resulted in placing the bulk of the points at the two extremes of the distribution may have exaggerated the deviation from normality.

It is thought to be improbable that the first conclusion is correct, since the backlog of experience in this laboratory has shown that in every other case the distribution of stress with percentage of failures has been normal. The possibility of the distribution being normal with respect to log S was investigated for this case, but no better fit was obtained.

The possibility that some unrecognized experimental difference was present for the tests at 36,000 psi is possible, although recheck of the data revealed no significant difference in hardness of the specimens at this stress and nothing unusual in the test procedure was recorded in the test log. However, examination of the data in table III shows that the standard deviation almost doubled between 36,000 and 35,000 psi. Experience, borne out by the data for the spheroidized structure, shows that σ often increases greatly when the stress is within the endurance range. If the probit regression line is redetermined, assuming

100-percent failure at 36,000 psi, the χ^2 test gives a probability of $P \approx 0.30$, thus satisfying the requirement of a normal distribution. The mean endurance limit is practically unchanged for this situation, but the standard deviation of the endurance limit decreases from 960 psi to 570 psi. With this lower value of σ, there is a statistically significant difference between the variability of the endurance limit of the spheroidized and pearlitic structures, as determined by the t test.

However, since there is no strict justification for the above conclusion, the view which has been adopted is that the observed result is a freak accident of sampling which would show a normal distribution and probably a smaller standard deviation if repeated with additional identical specimens.

Aluminum Alloys

The fatigue statistics obtained in this investigation for 24S alloy in two heat-treated conditions and 2S aluminum are presented in table IV and plotted in figure 4. Additional statistics which were calculated from recent published data for 75S alloy are given in table V and plotted in figure 5. These data serve to confirm the findings of this investigation and provide information on another particularly important aluminum alloy.

For all of these alloys application of the F test shows that the scatter increases significantly with decrease in stress. Therefore, in comparing the scatter in fatigue life between the aluminum alloys and other materials, it is necessary to make the comparisons at equivalent stress levels. This was done for the eutectoid steel by applying the F test to the data at stresses which were equal percentages of the endurance limits of the two structures. Unfortunately, commercial aluminum alloys show no endurance limit but rather have an S-N curve which slowly decreases in stress with large increases in the number of cycles to failure. No indication that an endurance limit exists for these materials was found when a large number of specimens were tested at rather low stresses. Since the results which would be obtained by comparing standard deviations with the F test would depend on the stress levels considered for each material, which in turn would depend on the particular values chosen for their endurance limits, it is felt that this method is not applicable for use with these materials. For example, using the F test to compare variances at 40 percent above the endurance limit, 24S-T4 aluminum was found to have greater scatter or less scatter than Armco iron, depending upon whether the value used for the endurance limit of the aluminum was 23,400 psi (obtained from extrapolation of the test data to 10^8 cycles) or 20,000 psi (Aluminum Company of America value for endurance limit at 5×10^8 cycles).

However, a qualitative indication of the scatter in fatigue life can be obtained with the relative standard deviation V (in percent). Epremian and Mehl (ref. 2) reported that for steels an average value of the relative standard deviation was 3 percent in the fracture range and 4 percent in the endurance range. Examination of tables IV and V shows that the relative standard deviations for 24S and 75S aluminum are comparable with those reported for steel. The lower values of V at the high stresses for 24S-T4 and 75S-T6 should not be taken as an indication that the scatter for these materials is lower than that for steel. The high stresses for these alloys represent a greater percentage endurance limit than that covered by Epremian and Mehl for steel, and hence the data for aluminum at these stresses are not directly comparable with any of their data.

The data for 2S aluminum appear to show slightly less scatter than that for the other alloys. The 24S and 75S alloys show large increases in scatter at stresses which produce a mean life near 10^7 cycles, while for 2S the scatter increases only slightly. It is interesting to note that the average V for 2S was 2.57 percent, which is almost identical with Ravilly's (ref. 5) average V of 2.58 percent. It is clear that the 2S aluminum shows less scatter in fatigue life than that reported for heat-treated steel.

DISCUSSION

Eutectoid Steel

It seems logical that metallurgical structure should play a role in determining fatigue properties and their statistical variation. In this investigation the effect of structure as determined by the morphology of the cementite phase has been isolated from the other variables. Since the spheroidized and pearlitic structures were produced from the same heat of eutectoid steel, the inclusion content may be presumed to be the same in both. The structures were at nearly the same tensile strength; therefore, their mean free ferrite paths are about equivalent. Hence, the lower endurance limit and significantly smaller scatter of the pearlitic structure must be attributed to the difference in morphology of the cementite phase between the two structures.

It has been recognized that particles of a second phase may, if they have sufficiently different properties from the matrix, act as stress concentrators for the initiation of fracture. The thin, angular cementite lamellae in pearlite are more severe stress concentrators than the more spheroidal carbide particles of the spheroidized structure. Further, the cementite lamellae are more readily fractured than the spheroidized carbides. Therefore, the lower endurance limit of the pearlitic structure is attributed to the much greater state of internal stress concentration produced by the cementite lamellae.

It has been shown that the larger the total number of defects, the less the scatter in the fracture strength. Such reasoning was used by Epremian and Mehl (ref. 2) in their use of a distribution of imperfections (inclusions) to explain the fact that scatter in fatigue life decreases with increase in stress level. The same reasoning may be readily applied to the case at hand. For two specimens of opposite structure with equal volume of second-phase carbide particles, an application of the same nominal stress to both structures would result in a higher internal stress condition in the pearlitic structure. Thus, for a given distribution of second phase, the pearlitic structure would have a greater number of effective defects and, hence, would have the smallest scatter in the number of cycles to fracture.

Aluminum Alloys

An important reason for the investigation of aluminum alloys was to test the conclusion made previously by Epremian and Mehl (ref. 2) that aluminum shows less scatter in fatigue life than steel, presumably because it is cleaner. Epremian's observation was based on a calculation from Ravilly's data (ref. 5) for torsional fatigue tests on an unspecified aluminum alloy. Obviously, the data presented herein for 24S and 75S alloys do not show less scatter than that found for steel. The data for 2S aluminum do show a lower scatter. There appears to be no significant difference in scatter between age-hardened 24S-T4 and annealed 24S-O. The microstructural differences between the two are not great. The 24S-O structure consists of a fine precipitate of $CuAl_2$ distributed uniformly throughout the grains. This precipitate is not present on a microscopic scale for the 24S-T4.

The question of whether inclusions are active in promoting scatter in aluminum alloys is not completely settled. For aluminum alloys what would correspond to nonmetallic inclusions in steel are not actually foreign particles but are considered a constituent formed from the elements of low solubility present in the alloy. Thus, for 24S and 75S alloys this constituent would be hard particles of an Fe-Al-Si ternary constituent. These particles are generally much more spherical than silicate inclusions in steel, they are smaller, but they are present in much greater numbers. The SAE method of rating inclusions in steel does not give a true representation of the content of impurity constituent in aluminum. The SAE inclusion rating for 24S aluminum would be $1^{vd} - 1^{21} - D^{+}$, which would be a low inclusion rating for steel. However, the background rating, based on those particles which are not larger than 1/2 inch when projected at 100 diameters, is much greater than that generally found for steel. Thus, it is not exact to state categorically that aluminum is cleaner than steel. Certainly the fatigue statistics for 24S and 75S alloys do not bear this out.

CONCLUSIONS

The fatigue statistics have been determined for a plain carbon eutectoid steel heat-treated to coarse spheroidized and coarse pearlitic structures of the same tensile strength and for 24S-T4, 24S-O, and 2S aluminum alloys over the range of 10^5 to 10^7 cycles. Calculation of data from the literature provided statistics for 75S-T6 aluminum alloy. The following conclusions are indicated:

1. The pearlitic structure has a decidedly lower endurance limit than the spheroidized structure of the same tensile strength.

2. The scatter in fatigue life was significantly less for the pearlitic structure.

3. The scatter in endurance limit was much less for the pearlitic structure. The difference was not statistically significant, although it is felt that the difference would be significant were it not for a peculiar sampling chance.

4. The scatter in fatigue life for 24S and 75S alloys was comparable with that generally found for steel; the 2S aluminum showed slightly less scatter than the other aluminum alloys and steel.

5. The scatter in fatigue life increases significantly with decrease in stress level for all of the materials studied, for both aluminum and steel.

Carnegie Institute of Technology,
Pittsburgh, Pa., September 30, 1952.

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TABLE I

MECHANICAL PROPERTIES OF EUTECTOID STEEL

[Prior austenitic grain size, A.S.T.M. 6; inclusion rating (SAE method), $4^{vd} - 1.8^{200vd} - C$]

Structure	Ultimate strength, psi	Yield strength, psi	Elongation, percent	Reduction in area, percent	Rockwell hardness
Spheroidite	92,680	[a]71,130	28.9	57.7	B-92
Pearlite	98,180	[b]35,500	17.8	25.8	B-89

[a]Lower yield point.
[b]0.1-percent offset.

TABLE II

MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

Alloy	Ultimate strength, psi	Yield strength (0.2-percent offset), psi	Elongation, percent	Reduction in area, percent	Brinell hardness
[a]24S-T4	65,400	40,950	23	34	93
[b]24S-O	32,275	12,680	22	42	42
[b]2S	15,700	------	40	--	25

[a]Average of five tests.
[b]Average of four tests.

TABLE III

FATIGUE STATISTICS FOR EUTECTOID STEEL

[Tested on R. R. Moore machines at 8,000 to 10,000 rpm]

Stress, psi	$\overline{\text{Log N}}$	Mean life, $\bar{N}$	Unbiased standard deviation, σ	Standard estimate of error, $\sigma_{\overline{\log N}}$	Relative standard deviation, V, percent	Failures, percent
Spheroidized eutectoid steel[a]						
47,500	5.33315	2.153×10^5	0.1644	0.0367	3.09	100
45,000	5.81040	6.462×10^5	.2797	.0253	4.82	95
43,000	5.92829	8.478×10^5	.2743	.0665	4.63	85
41,500	6.24127	1.743×10^6	.2713	.0904	4.35	45
40,000	-------	-----------	------	------	----	21
Pearlitic eutectoid steel[b]						
42,000	5.18280	1.53×10^5	0.0696	0.0174	1.35	100
38,800	5.57452	3.75×10^5	.0823	.0184	1.48	100
36,000	6.07108	1.21×10^6	.0920	.0217	1.51	90
35,000	6.29904	1.99×10^6	.1644	.0387	2.61	90
34,000	6.51126	3.24×10^6	.3420	.0987	5.25	50
33,500	-------	----------	------	------	----	10
32,500	-------	----------	------	------	----	5

[a]Mean endurance limit $\bar{S}$, 41,550 psi; σ endurance limit, 1,750 psi.

[b]Mean endurance limit $\bar{S}$, 34,000 psi; σ endurance limit, 960 psi.

TABLE IV

FATIGUE STATISTICS FOR ALUMINUM ALLOYS

[Tested on General Electric vibrating-cantilever machines]

Stress, psi	$\overline{\text{Log N}}$	Mean life, $\bar{N}$	Unbiased standard deviation, σ	Standard estimate of error, $\sigma_{\overline{\log N}}$	Relative standard deviation, V, percent
24S-T4 (naturally age-hardened)					
32,400	5.06010	1.15×10^5	0.0949	0.0254	1.87
26,400	6.21458	1.63×10^6	.1147	.0250	1.84
24,700	6.71513	5.19×10^6	.2575	.0575	3.83
24S-O (annealed)					
17,200	5.36584	2.32×10^5	0.1332	0.0298	2.48
15,100	5.49396	3.12×10^5	.1230	.0263	2.24
12,600	6.16192	1.45×10^6	.2305	.0516	3.72
12,200	6.92098	8.34×10^6	.5584	.1281	8.06
2S					
11,000	5.43156	2.70×10^5	0.1237	0.0276	2.28
9,000	6.57186	3.73×10^6	.1773	.0443	2.63
8,000	6.99655	9.93×10^6	.1961	.0449	2.81

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TABLE V

FATIGUE STATISTICS FOR 75S-T6 ALLOY

[Rotating-cantilever-beam machines]

Stress	$\overline{\text{Log N}}$	Mean life, $\overline{N}$	Unbiased standard deviation, σ	Standard estimate of error, $\sigma_{\overline{\log N}}$	Relative standard deviation, V, percent
[a]62,500	4.2040	1.6×10^4	0.036	0.0079	0.9
[a]50,000	5.000	1.0×10^5	.0702	.0140	1.4
[b]45,000	5.2890	1.94×10^5	.2024	.0491	3.82
[b]40,000	5.3881	2.44×10^5	.3184	.0732	5.92
[a]37,500	6.3570	2.3×10^6	.193	.0423	3.0
[b]35,000	6.1674	1.47×10^6	.2344	.0568	3.8
[b]30,000	7.2108	1.62×10^7	.4113	.0545	5.7

[a]Data from Yen and Dolan (ref. 6); 0.140-in.-diam. specimen.

[b]Data from Dolan and Brown (ref. 7); 0.150-in.-diam. specimen.

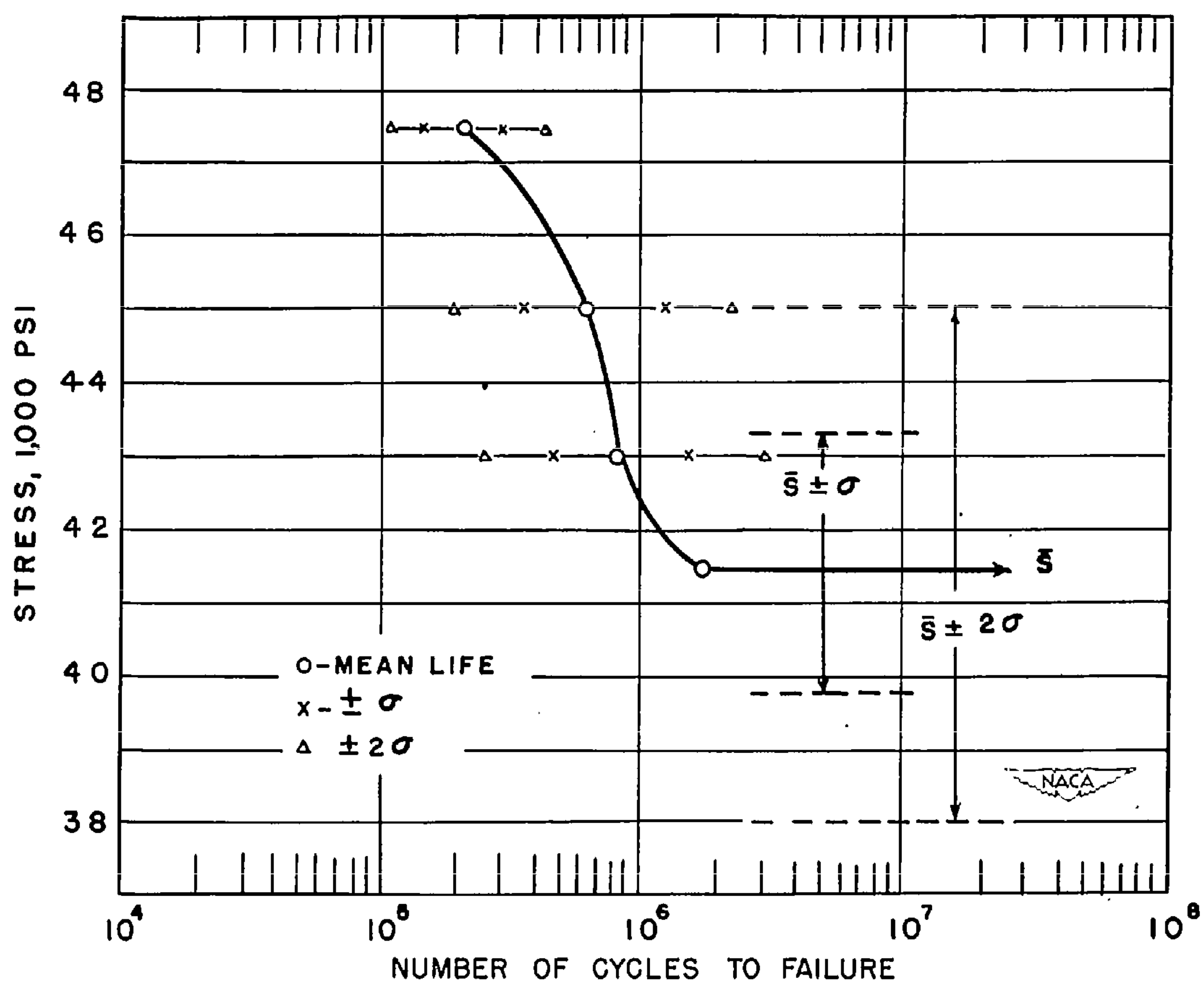

Figure 1.- Fatigue statistics for spheroidized eutectoid steel.

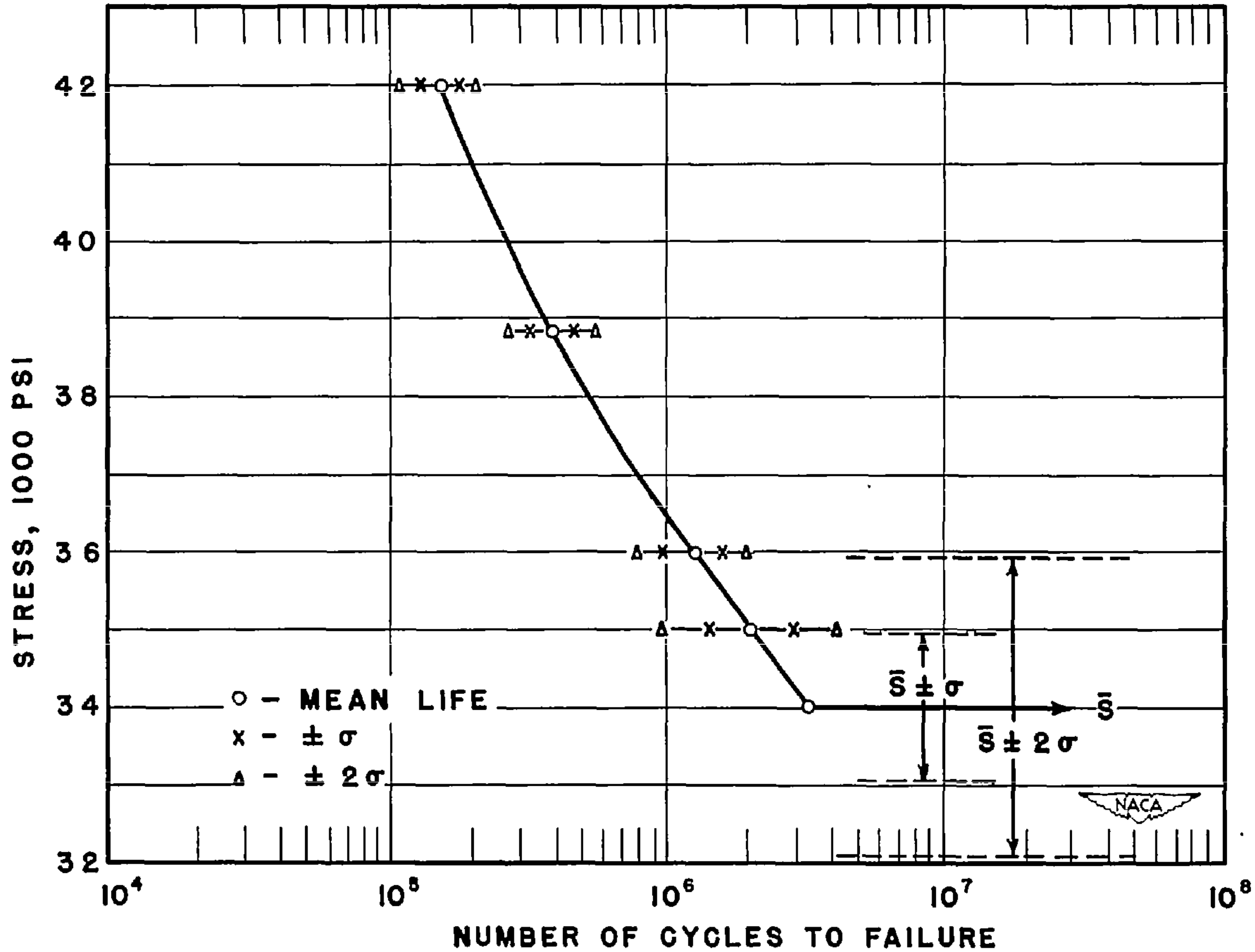

Figure 2.- Fatigue statistics for pearlitic eutectoid steel.

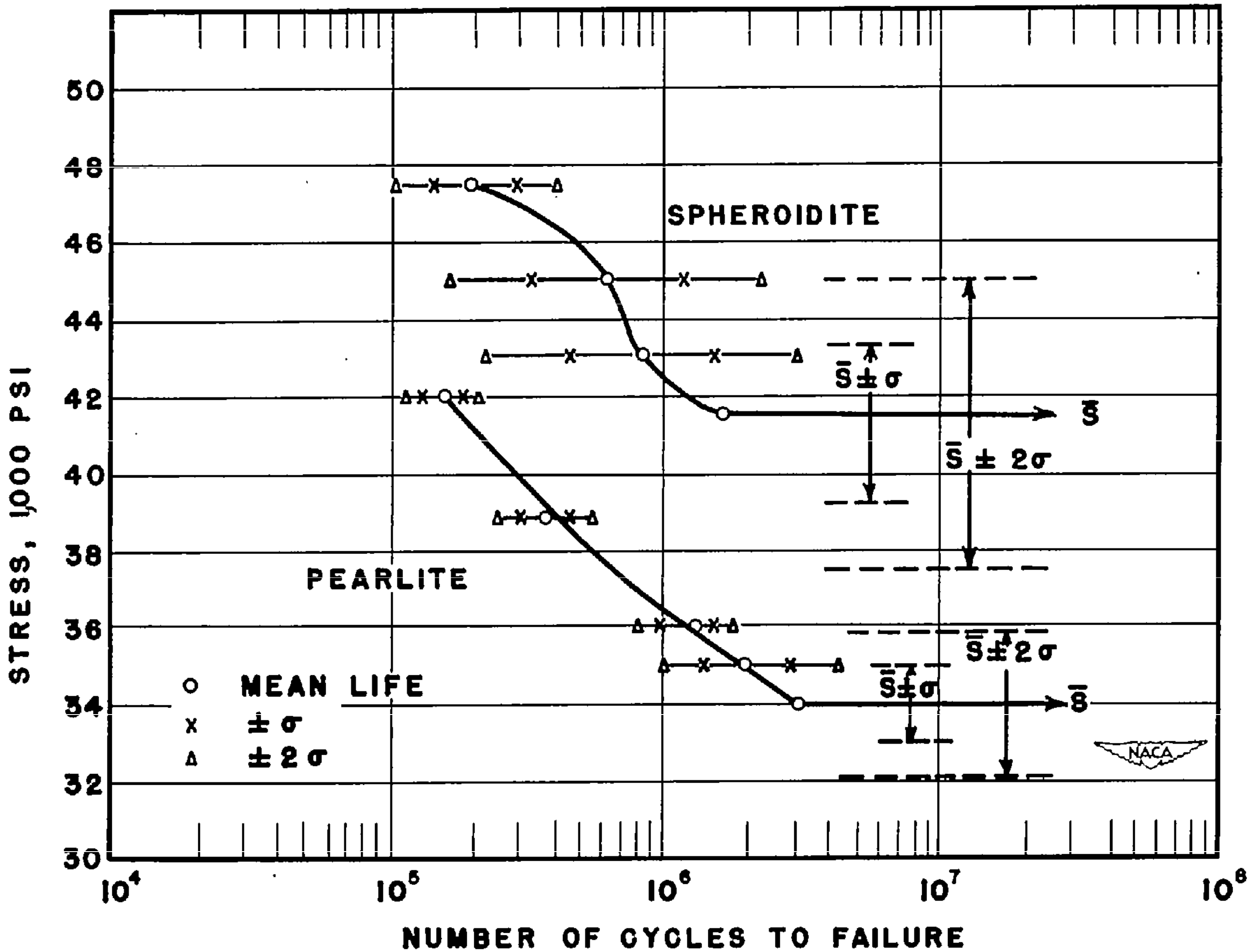

Figure 3.- Summary plot for eutectoid steel.

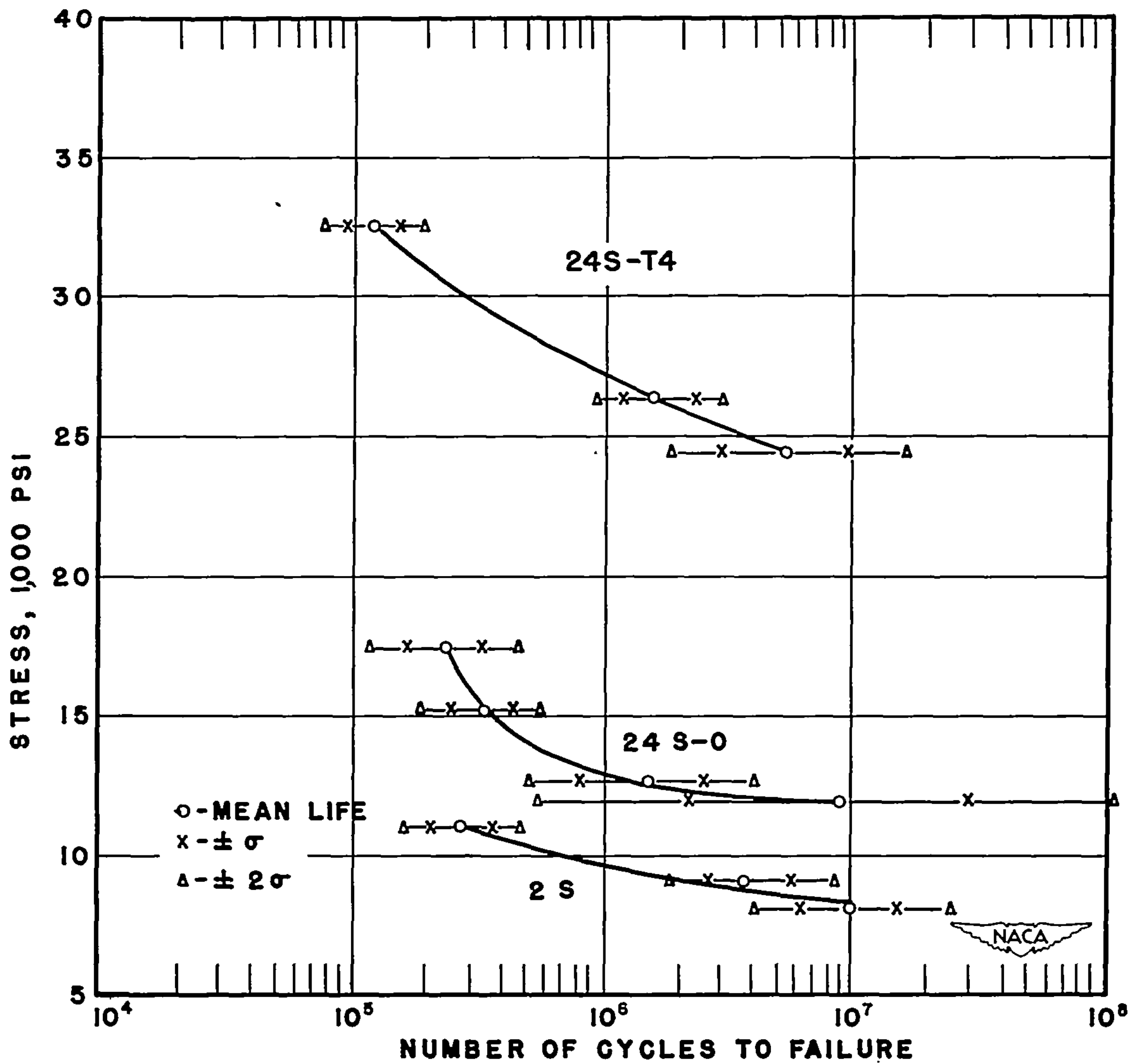

Figure 4.- Summary plot for aluminum alloys.

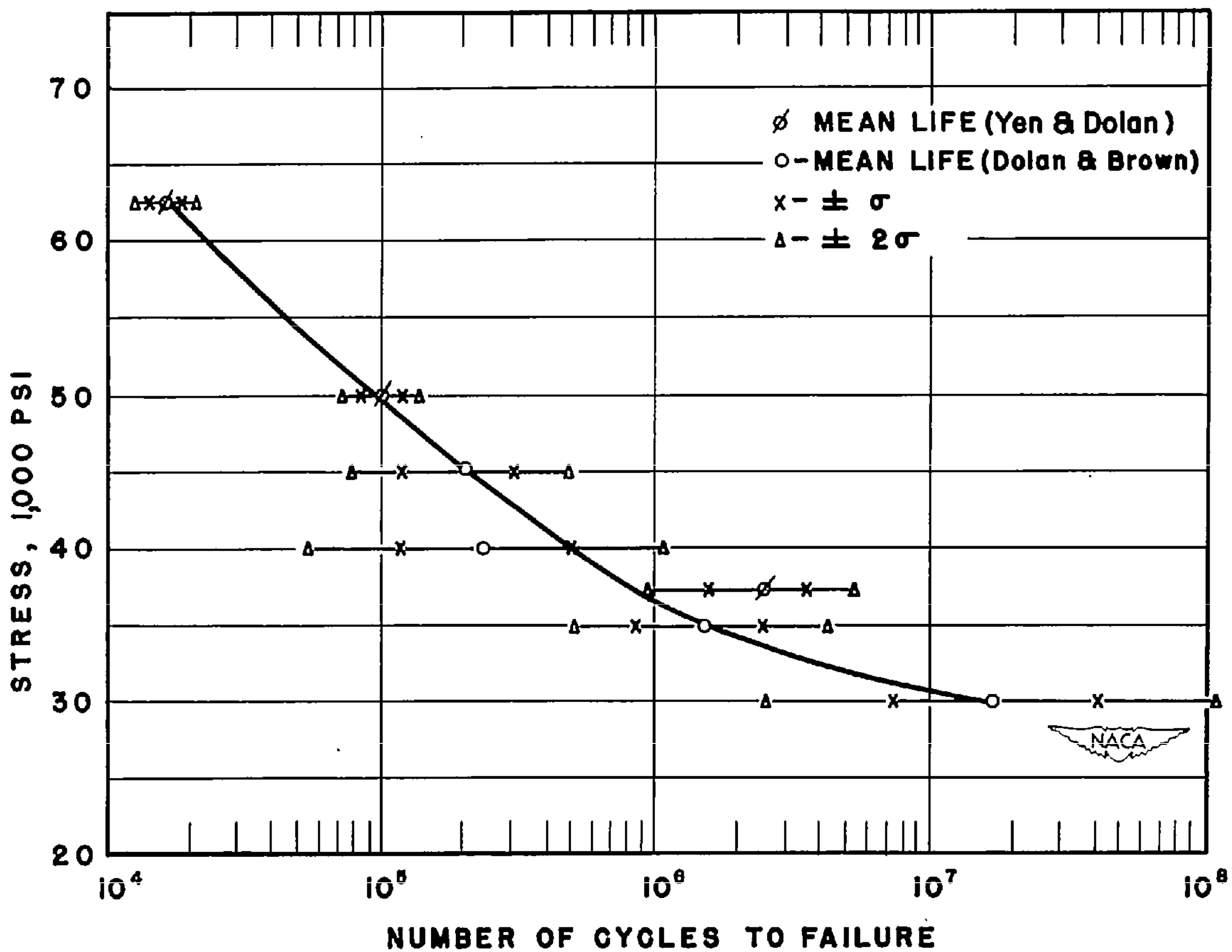

Figure 5.- Fatigue statistics for 75S-T6 aluminum. (Calculated from references 6 and 7.)