V. References

[1] G. D. Pinching and R. G. Bates, J. Research NBS **45**, 322 (1950) RP2142.
[2] R. G. Bates, J. Am. Chem. Soc. **70**, 1579 (1948).
[3] H. S. Harned and R. W. Ehlers, J. Am. Chem. Soc. **55**, 2179 (1933).
[4] R. G. Bates and G. D. Pinching, J. Research NBS **42**, 419 (1949) RP1982.
[5] E. Hückel, Physik. Z. **26**, 93 (1925).
[6] W. Ostwald, Z. physik. Chem. **3**, 241 (1889).
[7] A. Crum Brown and J. Walker, Ann. **261**, 107 (1891).
[8] P. Walden, Z. physik. Chem. **8**, 433 (1891).
[9] G. L. Voerman, Rec. trav. chim. **23**, 265 (1904).
[10] G. F. White and H. C. Jones, Am. Chem. J. **44**, 159 (1910).
[11] J. Böeseken and P. E. Verkade, Rec. trav. chim. **36**, 167 (1916).
[12] G. H. Jeffery and A. I. Vogel, J. Chem. Soc., 21 (1935).
[13] F. Auerbach and E. Smolczyk, Z. physik. Chem. **110**, 65 (1924).
[14] H. T. S. Britton, J. Chem. Soc. **127**, 1896 (1925).
[15] M. Mizutani, Z. physik. Chem. **118**, 318 (1926).
[16] H. S. Simms, J. Phys. Chem. **32**, 1121 (1928).
[17] I. M. Kolthoff and W. Bosch, Rec. trav. chim. **47**, 861 (1928).
[18] R. Gane and C. K. Ingold, J. Chem. Soc. 1594 (1928).
[19] A. Ölander, Z. physik. Chem. **A144**, 49 (1929).
[20] R. Gane and C. K. Ingold, J. Chem. Soc. 2153 (1931).
[21] H. W. Ashton and J. R. Partington, Trans. Faraday Soc. **30**, 598 (1934).
[22] W. L. German and A. I. Vogel, J. Am. Chem. Soc. **58**, 1546 (1936).
[23] I. Jones and F. G. Soper, J. Chem. Soc. 133 (1936).
[24] M. Duboux and D. Tsamados, Helv. chim. Acta **7**, 855 (1924).
[25] H. M. Dawson, G. V. Hall, and A. Key, J. Chem. Soc. 2844 (1928).
[26] H. S. Harned and R. A. Robinson, Trans. Faraday Soc. **36**, 973 (1940).
[27] T. L. Cottrell and J. H. Wolfenden, J. Chem. Soc. **1019** (1948).

WASHINGTON, JULY 6, 1950.

Journal of Research of the National Bureau of Standards   Vol. 45, No. 6, December 1950   Research Paper 2157

Effects of Prior Static and Dynamic Stresses on the Fatigue Strength of Aluminum Alloys

By John A. Bennett and James L. Baker

Tests made on specimens of Alclad 24S–T sheet showed that prior static load had a marked effect on the fatigue strength in unidirectional bending when the stress amplitude was relatively small. From tests on bare 24S–T sheet, it was found that a few cycles at a stress amplitude of 17,000 lb/in.^{2} resulted in a large increase in the fatigue life at 20,000 lb/in.^{2} Damage tests for other combinations of stress amplitudes indicated that the damage was nearly a linear function of ratio of the number of cycles at a given stress to the number that would cause failure at that stress. A new design of specimen and a new form of stress versus number of cycles to fracture (*S-N*) diagram are described.

I. Introduction

The phenomenon of fatigue failure in metals remains incompletely understood, despite the extensive research that has been done on the subject. In particular, the mechanism by which a small volume of metal is damaged by repeated stressing until a crack forms may be considered one of the outstanding mysteries in the mechanical behavior of materials. The purpose of the work reported in this paper was to evaluate some of the factors involved in this damaging process by using aluminum alloy specimens. As there appears to be no reliable means of measuring fatigue damage except by a fatigue test, this evaluation was carried out largely by means of tests at two stress levels.

Many investigators have reported experimental data showing the effect of dynamic stressing at one amplitude on the fatigue strength at a second amplitude, but the data for aluminum alloys are not in good agreement. Miner [1] [1] found in testing 24S-T that the damage was proportional to the cycle ratio [2] within the experimental error. On the other hand, Stickley [2, 3] reported that the fatigue strength of 17S-T rod could be increased by prestressing at a stress amplitude slightly below the test stress. Likewise, Work & Dolan [4] found an increase in fatigue life due to stressing at small amplitudes. However, Dolan, Richart, and Work [5] found for 17S-T that the fatigue life under gradually varying load cycles was greater when the minor stress amplitude was 18,000 lb/in.^{2} than when it was decreased to 16,000 lb/in.^{2}

These results do not give any consistent picture of the progress of fatigue damage in aluminum alloys, and it was the purpose of this work to evaluate this progress in much the same way that it was done for SAE X4130 steel in the investigation reported in [6].

One of the most interesting phenomena associated with fatigue is the improvement due to understressing. In ferrous materials this improvement increases as the amplitude of the understress approaches the fatigue limit. Aluminum alloys have no fatigue limit, and the effect of understressing is not so marked, but it is known to cause an increase in fatigue strength under certain conditions. It seemed reasonable that during the course of a fatigue test at relatively low stress there must be a reversal in the

---

[1] Figures in brackets indicate the literature references at the end of this paper.

[2] Cycle ratio is defined as the ratio of the number of cycles at a given stress amplitude to the number necessary to cause failure at that amplitude. Failure may be defined as either the beginning of a crack or complete fracture.

type of process taking place, with improvement occurring during the early part of the test, and damage later. In order to investigate this, one of the prestress amplitudes chosen was low enough so that the number of cycles to fracture would be very large.

When a metal is subjected to fluctuating stress, there are presumably two opposing processes taking place, namely, work-hardening and fatigue damage. While the mechanism of fatigue damage may involve repeated plastic deformation of a microscopic volume of the metal, this is apparently distinct from the process that is usually referred to as work-hardening. It is to be expected that the greater part of this over-all hardening would be completed in a relatively few cycles at the start of the dynamic stressing. For this reason, it was decided to make tests after a very small number of cycles in order to detect changes due to work-hardening.

A few tests were made to determine the changes in fatigue properties caused by static stressing, prior to testing, for comparison with the changes caused by dynamic stressing prior to testing. In order to make the effect as pronounced as possible, the tests were made on Alclad 24S-T; the soft cladding would be expected to deform plastically at a lower stress than the core, producing a residual stress that would influence the fatigue properties.

Fatigue tests usually are performed by applying the fluctuating load until the specimen fractures. The life of the specimen, as determined by such a test, includes both the period of increasing damage, which culminates in the formation of a crack, and the period of crack growth, which ends with the fracture of the specimen. In order to study the first period without having the results confused by the second, it is necessary to determine as nearly as possible the point at which the crack forms.

II. Materials and Test Methods

All of the tests reported here were made on Krouse sheet bending fatigue testing machines. These machines are designed to load the specimen as a cantilever, the range of deflection being determined by the setting of an adjustable eccentric and the mean load by the adjustment of the movable vise. The amplitude of deflection remains constant during the course of the test, so that any change in the resilience of the specimen results in a change in the applied stress.

The materials used in this investigation were bare and Alclad 24S-T sheet. For the tests reported in sections III and IV, the materials were obtained commercially. For the study of damage reported in section V, the 24S-T sheet was obtained from the NACA Langley Aeronautical Laboratory from a stock maintained especially for fatigue research.

The two types of specimens used are shown in figure 1, a and b. The first is the standard type of specimen recommended by the testing machine manufacturer, while the second is a modification adopted for the reasons given in section IV. The over-all dimensions of the two specimens were the same, and the methods of test were identical. The specimens were cut with the long dimension parallel to the direction of rolling.

There is a possibility of confusion of terms in referring to the various surfaces and lines that bound a specimen cut from sheet material; in this report the term face will be used to refer to the surfaces of the original sheet. The surfaces at right angles to the faces and roughly parallel to the long dimension of the specimen will be called the sides, and the intersection of a face and a side will be termed an edge.

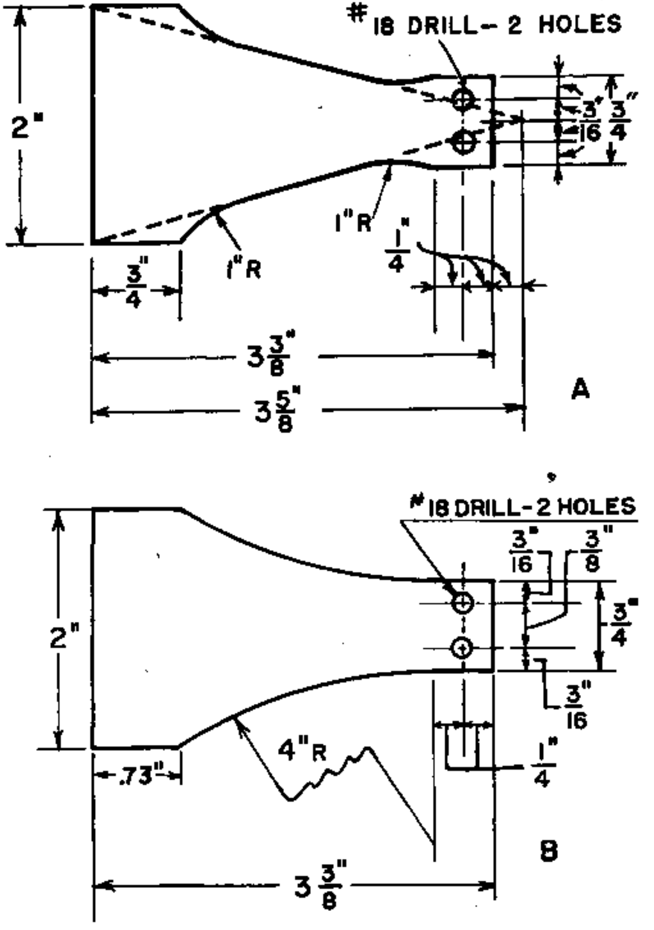

FIGURE 1. *Types of specimen used for bending fatigue tests on sheet materials.*

a, Standard specimen; b, modified specimen.

The edges of all specimens were manually polished with No. 400 Aloxite paper, the direction of polishing being parallel to the edge.

In both types of specimens the maximum stress in the reduced section was only about 25 percent greater than that at the point where the specimen was clamped in the vise. For this reason, there was some difficulty at first with the specimens breaking at the vise. This trouble was almost entirely eliminated by placing several thicknesses of greased paper between the specimen and the clamping plates to distribute the load. However, it is felt that in any future work with these machines it would be advisable to increase the width of the specimen at the vise to eliminate the need for this precaution.

The load necessary to produce a given stress in the specimen was calculated from the usual cantilever formula

$$P=\frac{Sd^2b}{6L},$$

where P is the load necessary to produce a given stress in the specimen; S is the nominal stress in the extreme fibers; d is the thickness of the specimen; b is the width of the specimen at a given point; and L is the distance from the point where the width is measured to the point at which the load is applied. The standard specimens had a reduced section that tapered toward the crank pin where the load was applied. This resulted in a constant nominal stress in the reduced section, as both the width of the specimen and the bending moment are proportional to the distance from the point of application of the load.

The specimens of 4-in. radius had no straight side, so it was necessary to use a special jig to determine the minimum value of the ratio b/L in the above formula. The jig is shown in figure 2. The pivot on which the vanes turn was at the same distance from the end of the specimen as the crank pin of the machine, and the extended edges of the vanes passed through this pivot. Therefore, if the vanes were rotated until they were tangent to the edges of the specimen, the point of tangency was the point of minimum b/L ratio. In use the jig was clamped to the table of a toolmaker's microscope and the length of the jig alined with the longitudinal measuring screws. Then the vanes were rotated until only a narrow gap remained between each vane and the corresponding edge of the specimen. The width of the specimen was measured near the center of this gap by using the transverse measuring screw, and the distance to the center of the pivot was measured with the longitudinal screw. In the figure a broken specimen is shown in place on the jig to indicate how the typical fracture occurred near the point of minimum b/L ratio.

III. Effect of Prior Static Load on the Fatigue Strength of Alclad 24S–T

The material used in this investigation was obtained commercially, and the surface was badly scratched and dented. These defects, however, did not appear to influence the fatigue test results. All of the tests were made in unidirectional bending with the mean load equal to half the maximum. The stress values given in this section refer to the maximum nominal stress in the cycle. The standard type of specimen (fig. 1, a) was used.

In order to obtain the basic S-N curve, 24 specimens were tested at the following nominal stresses; 20,000, 25,000, 30,000, and 35,000 lb/in.^{2} These results are shown in the first line of table 1 and are represented by the curve (not the points) on figures 3 and 4.

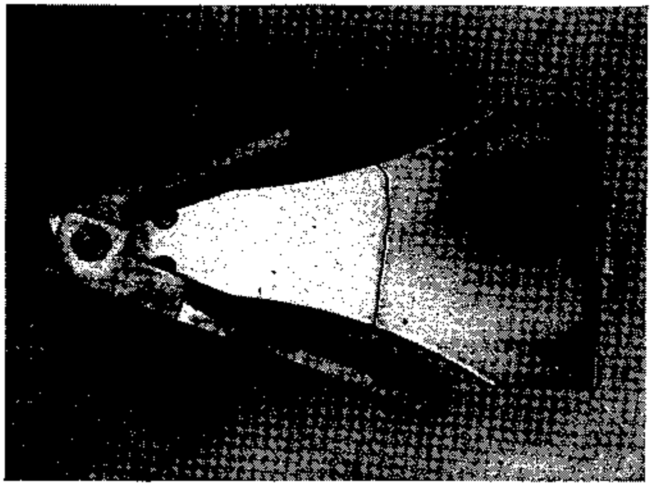

FIGURE 2. *Four-inch radius specimen in place on measuring jig.*

A broken specimen is shown in order to illustrate how the fractures occurred near the point of minimum b/L ratio.

The effect of prior static load was then determined for four conditions of loading, as follows: (1) static load corresponding to a nominal stress of 30,000 lb/in.^{2} applied in the same direction as the subsequent fatigue test load; (2) the same load applied in the direction opposite to that of the subsequent fatigue test load; (3) static load corresponding to a nominal stress of 40,000 lb/in.^{2} applied in the same direction as the subsequent fatigue test load; and (4) the same load applied in the opposite direction. In each case the prior static load was allowed to remain on the specimen for approximately 1 minute, then the fatigue test was started as soon afterward as possible. In most cases two specimens were tested for each load condition, the values given in table 1 being

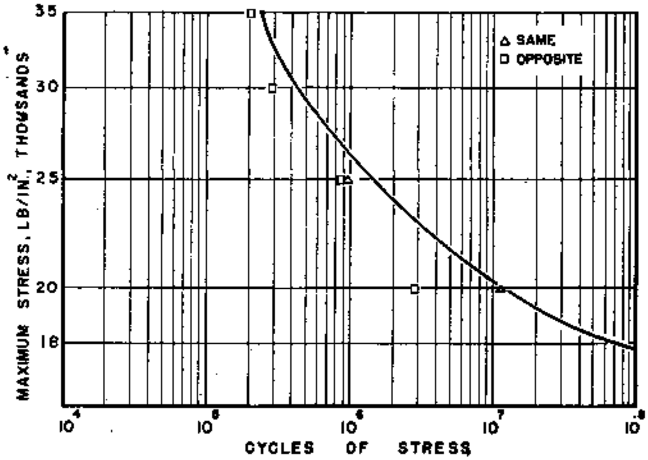

FIGURE 3. *Effect of prior static stress (nominal maximum value 30,000 lb/in.^{2}) on the fatigue properties of Alclad 24S–T sheet in unidirectional bending.*

Solid curve represents data for original material; squares are averages for specimens prestressed in direction opposite to test stress, triangles are averages for specimens prestressed in same direction as test stress.

Table 1. *Effect of prior static stress on the fatigue strength of Alclad 24S-T sheet*

(Fatigue test in unidirectional bending. Minimum stress = 0, maximum nominal stress is listed)

Nominal static prestress	Direction of loading [a]	Average number of cycles to fracture at test stresses listed											
		No. of tests	20,000 lb/in.^{2}	Range of values	No. of tests	25,000 lb/in.^{2}	Range of values	No. of tests	30,000 lb/in.^{2}	Range of values	No. of tests	35,000 lb/in.^{2}	Range of values
lb/in.^{2}													
None		6	11,723×10^3	13,693×10^3	4	1,489×10^3	1,002×10^3	8	461×10^3	221×10^3	6	253×10^3	26×10^3
30,000	Same	4	10,763	6,628	1	927							
40,000	do	2	23,660	2,885	2	920	284	2	367	64	3	222	49
30,000	Opposite	3	2,788	1,024	2	878	75	2	286	15	1	207	
40,000	do	2	2,166	448	2	677	34	2	508	149	2	255	76

[a] Direction of prior static load relative to fatigue test load.

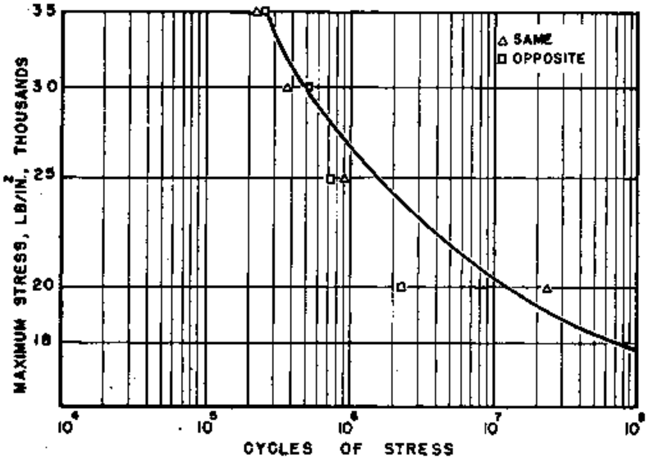

Figure 4. *Effect of prior static stress (nominal maximum value 40,000 lb/in.^{2}) on the fatigue properties of Alclad 24S-T sheet in unidirectional bending.*

Solid curve represents data for original material; squares are averages for specimens prestressed in direction opposite to test stress, triangles are averages for specimens prestressed in same direction as test stress.

the averages of the number of cycles to failure for the specimens tested under identical conditions. In figure 3 the results for the specimens tested after a static stress of 30,000 lb/in.^{2} are shown as individual points for comparison with the curve representing the fatigue properties of the original material, while the points in figure 4 represent the data for a prior static stress of 40,000 lb/in.^{2} It should be emphasized that the stress values given here are calculated on the basis of elastic bending of the specimen. As there is considerable plastic deformation, particularly at the higher loads, these nominal values of stress are undoubtedly considerably different from the true stress. However, these values do indicate the magnitude of the bending moments applied to the specimens, which are significant from a practical standpoint.

The results indicate that there was little or no effect except at the lowest test stress used (20,000 lb/in.^{2}). At this stress (20,000 lb/in.^{2}) the effect was quite marked; for example, with a prior static stress of 40,000 lb/in.^{2} the specimens loaded in the same direction as the fatigue test load endured 10 times as many cycles before fracture as those loaded in the opposite direction.

IV. Effect of Specimen Geometry on Results of Bending Fatigue Tests

As a result of the tests reported in the preceding section and other bending fatigue tests made previously, it was thought that the form of specimen commonly used in this type of machine had certain disadvantages. Although it is designed to have a section in which the stress is nominally constant, this section is bounded by fillets that raise the actual stress sufficiently to cause most of the failures to originate at the bottom of one of the fillets. Accordingly, it was thought better to make the specimens with each side formed by a single circular arc of large radius, and the design finally adopted is shown in figure 1, b. The reasons for selecting the value of 4 in. for the radius were as follows: (1) This is the largest radius that could be used with essentially the same over-all dimensions as the standard specimen; (2) it is sufficiently large so that the stress concentration due to the radius is negligible; (3) a sheet specimen having the reduced section formed by an arc of 4-in. radius on each side is being used for axial load fatigue tests in the Engineering Mechanics section of this Bureau, and it was thought that future comparisons of data would be simplified by having a similar reduced section on the sheet bending specimens; (4) it was desirable to have a radius that could be used also for R. R. Moore and axial load fatigue specimens, and new type specimens for these machines have been designed with a 4-in. radius; (5) 8-in. diameter milling cutters are readily available, so that the specimens could be milled with a single traverse of the cutter on each side. This factor is important in reducing the cost of the specimens.

In order to compare the results obtained with the two designs, 20 specimens of each type were prepared from a sheet of 24S–T nominally 0.102-in. thick. The results of fatigue tests made on these specimens are shown in table 2 and figure 5. All tests were made in completely reversed bending. Three specimens of each shape were tested at each of the four test stresses to determine the approximate relationship of the fatigue strengths, then seven additional specimens of each design were tested at a stress amplitude[3] of

---

[3] To avoid confusion it should be pointed out that the term *amplitude* is used here to mean the value of A in the equation for the stress at any time, t,

$$S=A\ (\sin 2\pi ft+B,$$

where f is the frequency of the testing machine, and B is the mean stress.

25,000 lb/in.^{2} in order to obtain a more accurate comparison of the dispersion of the data.

The fatigue strength of the 4-in. radius specimens was consistently higher than that of the standard specimens, although the difference was not large. The stress to cause fracture in a given number of cycles was, on the average, 5 percent higher for the new type specimens than for the straight tapered ones, the difference being greater the larger the stress amplitude. This difference might be ascribed either to the lower stress concentration in the 4-in. radius specimen or to an effect analogous to size effect, considering that the new specimen has a smaller volume of metal to which maximum stress is applied. If the latter factor were the chief consideration, it would be expected that the dispersion of the results for the tapered specimens would be less than that of the 4-in. radius type. However the coefficients of variation in table 2 indicate that the opposite is true, and that there is quite a difference in favor of the latter type. On the basis of these results it was concluded that the 4-in. radius specimen was a more satisfactory design than the tapered one, both as regards elimination of stress concentration and reduction of scatter of the results. Accordingly, specimens of this type were used in all of the subsequent work reported in the following sections.

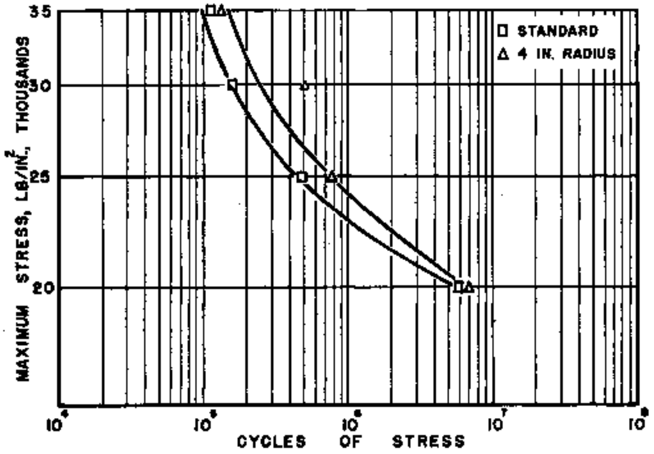

FIGURE 5. *Comparison of fatigue properties of 24S–T sheet obtained with standard and 4-in. radius specimens.*

TABLE 2.

A. Effect of specimen shape on fatigue strength of 24S–T sheet

Stress amplitude	Standard specimen		4-inch radius specimen	
	Number of tests	Average number of cycles to failure	Number of tests	Average number of cycles to failure
lb/in.^{2}				
20,000	3	5,871×10^3	3	6,644×10^3
25,000	10	493	10	743
30,000	3	146	3	536
35,000	3	113	3	132

B. Dispersion of data for a stress of 25,000 lb/in.^{2}

	Standard specimen	4-inch radius specimen
Average number of cycles to fracture $\overline{N}_F$	493×10^3	743×10^3
Standard deviation, σ[a]	319	289
Coefficient of variation, $100\sigma/\overline{N}_F$ (%)	65	39

[a] The values of standard deviation given here were computed by using the formula given on p. 14 of [9]:

$$\sigma=\sqrt{\frac{\Sigma(X_i-\overline{X})^2}{n}}.$$

The more common form of the equation is

$$\sigma=\sqrt{\frac{\Sigma(X_i-\overline{X})^2}{n-1}},$$

and this difference should be kept in mind in comparing these data with those reported by other investigators.

V. Evaluation of Fatigue Damage in 24S–T Sheet

It was intended that this study of fatigue damage would follow approximately the same course as that described in the latter part of [6]. However, the data proved to be much less reproducible than the R. R. Moore tests on steel, so the results could not be so readily analyzed and only limited general conclusions could be drawn from them.

The determination of the point at which a crack starts in a fatigue specimen requires two techniques not ordinarily employed in fatigue testing, namely, stopping the test when a small crack has formed, and measuring the growth of the crack with increasing numbers of cycles. This provides information for estimating the number of cycles between the start of cracking and the first observation of the crack. The method used for stopping the test when a small crack had formed was that described by Foster [8]. This involved cementing a small diameter wire on to the surface adjacent to the critical sections of the specimen. The wire carried the operating current to a relay controlling the testing machine motor, so that when the wire was broken the machine would be stopped. It was reported in the reference cited that the wire did not break until a crack had formed under it. This was not found to be the case with the sheet specimens in bending, although the conditions reported by Foster were duplicated as nearly as possible. Wires cemented onto the face of the specimens broke in as little as one-fourth the number of cycles required to start a crack in the specimen. This caused a considerable delay for inspection of the specimen and cementing another wire in place. Accordingly, the wires were usually cemented onto the side of the specimen, a short distance away from the edge where the strain amplitude was not so great. This had the disadvantage that a somewhat larger crack was required to break the wire than when it was on the face, but the sensitivity was considered adequate.

After a small crack had been detected with the fracture wire, measurements of the growth of the crack were made at intervals until final fracture.

Figure 6 shows typical curves of crack length (expressed in terms of the ratio of the crack length to the width of the specimen at that point) versus number of cycles for three specimens tested with a nominal stress amplitude of 30,000 lb/in.² The crack length was measured on the face of the specimen that had the longest crack, and the differences in the shapes of the curves in figure 6 are presumably due to differences in the development of cracks on the other face. The crack growth curves were extrapolated back to 0.01 crack-length ratio, and this was arbitrarily taken as the start of the crack. While this is obviously a rather approximate process for determining the start of cracking, the accuracy was considered adequate in view of the fact that the number of cycles from cracking to fracture was small in comparison to the number of cycles required to start the crack.

Several specimens were tested in the manner described above to determine the average number of cycles from cracking to fracture $\overline{(N_F-N_C)}$ (where N_F is the number of cycles at which the specimen fractured completely, and N_C is the number of cycles at which a crack first formed) at each of four stress amplitudes, 20,000, 25,000, 30,000, 35,000 lb/in.² These values were then subtracted from the average number of cycles to fracture for all specimens tested at the corresponding stress amplitude in order to arrive at the average number of cycles to form a crack, N_C. Both of these sets of data are shown in figure 7 and also are given in table 3. Three tests were made at a stress amplitude of 18,000 lb/in.² in order to obtain a better idea of the general shape of the *S-N* curve, but no determination of the start of cracking was made at this stress, as it was not to be used as a test stress in the evaluation of damage.

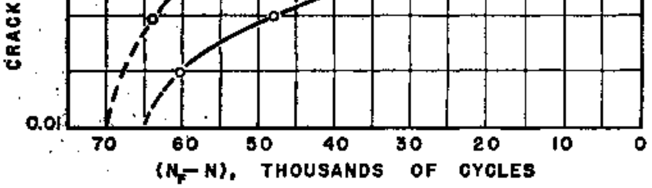

FIGURE 6. *Crack growth curves for 24S–T specimens tested at a nominal stress amplitude of 30,000 lb/in.²*

Crack length ratio is equal to the crack length divided by the specimen width.

TABLE 3. *Data for S–N curve, 24 S–T sheet*

Stress amplitude	Number of specimens	Average number of cycles from beginning of crack to fracture (N_F-N_C)	Number of specimens tested	Average number of cycles to fracture, N_F	Calculated number of cycles to produce crack $N_C^*=N_F-\overline{(N_F-N_C)}$
lb./in.²					
35,000	4	27×10^3	9	141×10^3	114×10^3
30,000	5	70	7	336	266
25,000	4	135	11	919	784
20,000	3	300	8	4,524	4,224
18,000	-------	-------	3	22,266	-------

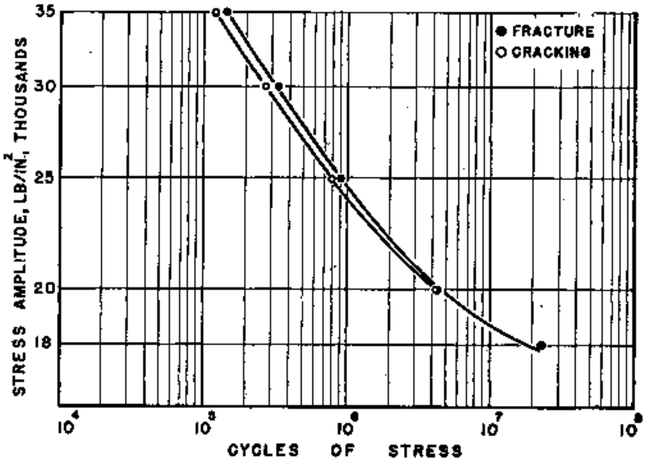

FIGURE 7. *S-N curves for cracking and fracture in 24S–T sheet specimens.*

The evaluation of fatigue damage was carried out by stressing a specimen for a predetermined number of cycles at one stress amplitude, then testing it to fracture at a second amplitude. The damage was defined as the percentage decrease in the number of cycles required to form a crack in the prestressed specimen as compared with the original material,

$$D=\frac{N_C-N_{CP}}{N_C}\times100,$$

where D is the percentage damage, and N_{CP} is the number of cycles at which a crack first formed in a prestressed specimen. None of the tests for the determination of N_C^* (calculated number of cycles to crack) had been made at the stress amplitudes chosen for the prestress, so the number of cycles to start of cracking had to be obtained by interpolation. To make this interpolation as accurate as possible, it was desirable to find a method of plotting the data that would give a straight line. As shown in figure 8, this condition was satisfied very closely by plotting the logarithm of N_C^* against the reciprocal of the stress, so the interpolation was performed on this basis.

Three prestress amplitudes were used, 17,000, 22,500, and 32,500 lb/in². For the lowest value, the number of cycles to start a crack was not known, so the numbers of cycles of prestress were arbitrarily selected as 2×10^3, 2×10^6 and 2×10^7. For the two higher stresses it was intended to apply the prestress for cycle ratios of 0.1, 50, and 90 percent. However, the number of cycles corresponding to the intended values of cycle ratio were determined on the basis of a group of tests made prior to starting the two-

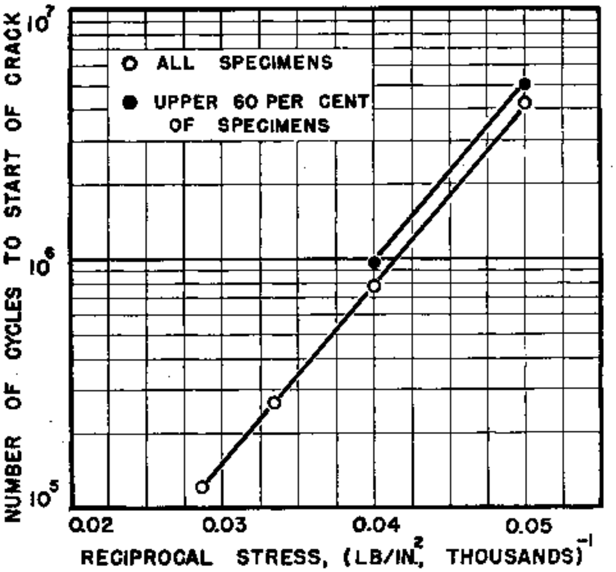

FIGURE 8. *Graph illustrating the linear relationship obtained when log N_C is plotted against the reciprocal of the stress amplitude.*

stress-level tests. Single-stress-amplitude tests were made of additional specimens after the damage tests had been started, and these changed the average values of N_C^*, so that the final values of cycle ratio were somewhat different from the intended ratios. The value of N_C^* originally obtained at 32,500 lb/in.^{2} was too low, so that the final cycle ratios are smaller than the intended values, whereas the reverse was true at 22,500 lb/in^2. In addition, the highest ratio at 22,500 lb/in^2. was altered as a result of specimens that failed before the prestressing was completed, as explained below. The final interpolated values of N_C^* which were used in determining cycle ratios were

Stress amplitude	N_C^*, 10^3 cycles
lb/in.^{2}	
22,500	1,650
32,500	175

The results of the damage tests are shown in figures 9, 10, and 11 and are listed in table 4. A negative value of damage indicates that the average life of the specimens that had been prestressed was greater than that of the original material at the same stress amplitude. There are two values of damage that exceed 100 percent; these are possible because the calculation of damage is based on N_C^*. If the average value of N_F for the prestressed specimens is less than the number of cycles from start of cracking to fracture, then the average N_{CP} will be negative, and the calculated damage will exceed 100 percent.

TABLE 4. *Summary of damage data, 24S–T sheet*

Test stress	2×10^3 cycles prestress		2×10^6 cycles prestress		2×10^7 cycles prestress	
	Number of specimens	Damage	Number of specimens	Damage	Number of specimens	Damage
	Prestress amplitude 17,000 lb/in.^{2}					
lb/in.^{2}		*Percent*		*Percent*		*Percent*
20,000	2	−448	3	−427	3	−33
25,000	3	65	3	−33	3	32
30,000	3	29	3	−3	3	43
35,000	3	14	3	26	3	11
	Prestress amplitude 22,500 lb/in.^{2}					
	0.1-percent cycle ratio		54-percent cycle ratio		80-percent cycle ratio	
20,000	4	−3	6	77	2	42
25,000	3	17	4	73	2	35
30,000	3	−9	3	62	5	−141
35,000	3	41	3	47	5	67
	Prestress amplitude 32,500 lb/in.^{2}					
	0.1-percent cycle ratio		42-percent cycle ratio		75-percent cycle ratio	
20,000	2	−8	3	48	3	77
25,000	5	58	3	57	4	105
30,000	3	−14	3	79	2	79
35,000	3	25	3	45	5	102

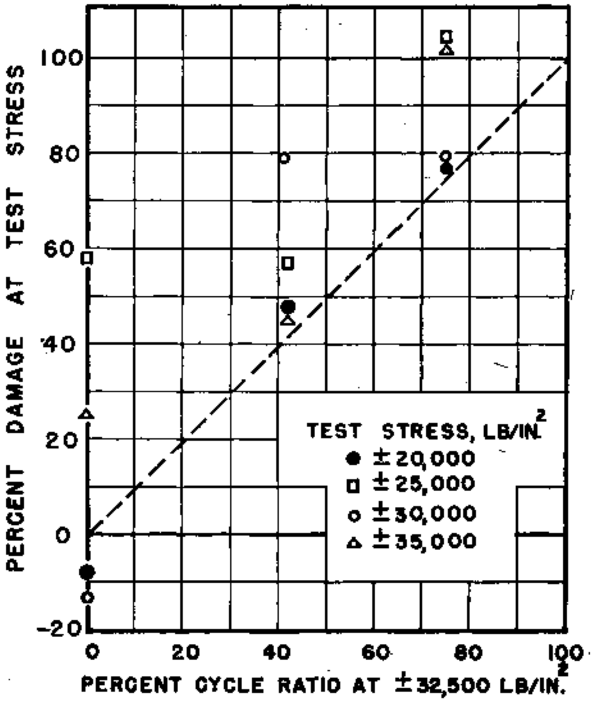

FIGURE 9. *Evaluation of fatigue damage due to prestressing at an amplitude of 32,500 lb/in^2.*

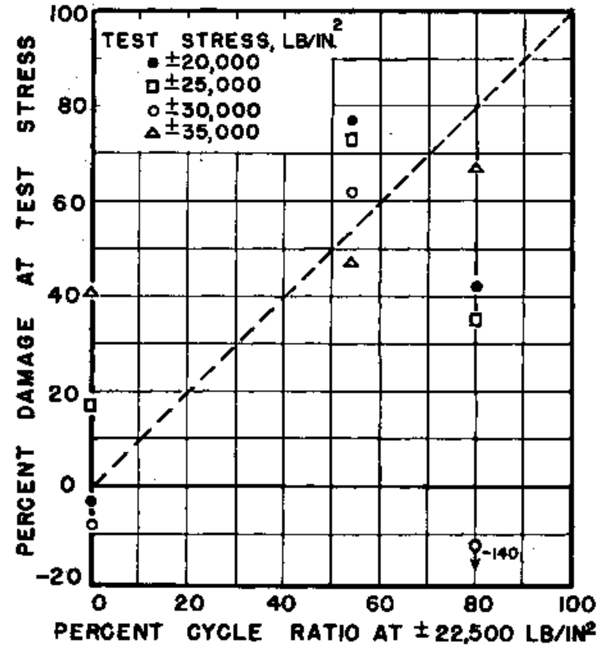

FIGURE 10. *Evaluation of fatigue damage due to prestressing at an amplitude of 22,500 lb/in^2.*

For the tests involving high cycle ratios, some of the specimens broke before the prestressing was completed. The corrections applied to the data to account for these failures are explained in the appendix.

It can be seen from the figures that the data were somewhat scattered. No attempt has been made to draw curves illustrating the trends of the data on figures 9 and 10, but a dashed line at 45° (representing a constant rate of damage) has been put on the figures for reference. While most of the points lie above this line, there is no consistency as to the relative position of the points representing the different test stresses. It appears also that the method of computing the cycle ratio for the largest number of cycles at ±22,500 lb/in.^{2} introduced an appreciable error, as these results are quite out of line with the others for this prestress amplitude.

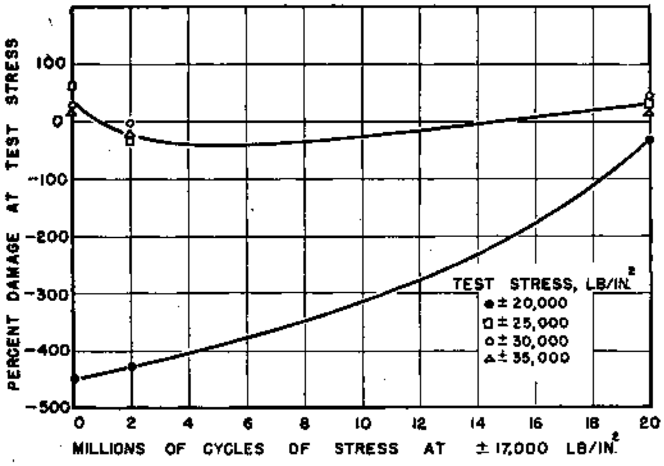

FIGURE 11. *Evaluation of fatigue damage due to prestressing at an amplitude of 17,000 lb/in^2.*

The effect of prestress at an amplitude of 17,000 lb/in.^{2} was more pronounced, and the scatter therefore less important. As shown in figure 11, there was an increase in fatigue life as a result of this prestressing, which was particularly marked at the lowest test stress. The effect at all of the other test stresses was of approximately the same magnitude, so that only a single curve has been drawn on the figure to represent these data.

VI. Discussion of Results

The results of the tests described above indicate that both static and dynamic stress applied prior to the start of a fatigue test can have a marked effect on the fatigue life at relatively low stresses. In the case of the Alclad material tested in unidirectional bending, the changes caused by static bending were probably largely due to residual stress in the outer fibers of the sheet. In the case of the bare material tested in reversed bending, the improvement caused by a small number of cycles of stress slightly below the test stress was probably caused by cold-working. In both cases it appeared that the beneficial effect was eliminated by the fatigue stressing at all amplitudes above the lowest value used in the tests.

The dispersion of the data was so great that it would have been impossible to obtain results as precise as those reported previously for steel [6] without using an unreasonable number of specimens. It is not known how much of the difference in the scatter of the data was due to inherent difference in the material and how much was caused by the specimen geometry, but certainly the latter factor would be important. It is much more difficult to obtain reproducible conditions on the edge of a sheet than on the surface of a cylindrical specimen.

VII. Conclusions

As a result of flexural fatigue tests made on 24S–T aluminum alloy specimens the following conclusions were reached.

1. The application of a static bending load to the specimens had a significant effect on the fatigue life of the specimens under unidirectional bending, if the stress amplitude in the fatigue test was small. For a large static load in the same direction as the fatigue load, the fatigue life was increased, while the reverse was true if the directions were opposite.

2. A new design of specimen, having each side formed by a circular arc of 4-in. radius, was found to be more satisfactory than the straight tapered design. The new specimens were cheaper to manufacture, had less stress concentration in the test section, and gave more-reproducible results than the standard type.

3. Fracture wires were found to be a satisfactory means of stopping these tests when a small fatigue

crack had formed, but their use involved some difficulties.

4. The dispersion of the results of flexural fatigue tests on aluminum alloys was much greater than that of rotating beam test results on steel previously reported.

5. The relation between the reciprocal of the stress and the logarithm of the number of cycles to the start of cracking was found to be linear.

6. For prestress amplitudes of 32,500 and 22,500 lb/in.^{2}, the precision of the data was not sufficient to justify an exact statement regarding the progress of fatigue damage. The assumption of a linear relation between cycle ratio and damage was within the experimental error.

7. Prestressing at a stress amplitude of 17,000 lb/in.^{2} resulted in an improvement in fatigue life, that is, the damage was negative. For specimens subsequently tested at a stress amplitude of 20,000 lb/in.^{2}, the improvement in fatigue life after either 2,000 or 2,000,000 cycles of prestress was more than 400 percent.

IX. References

[1] Milton A. Miner, Cumulative damage in fatigue, Trans. ASME **67**, A-159 to 164 (1945).

[2] G. W. Stickley, Effect of alternately high and low repeated stresses upon the fatigue strength of 25S-T aluminum alloy, NACA Tech. Note 792 (1941).

[3] G. W. Stickley, Improvement of fatigue life of an aluminum alloy by overstressing, NACA Tech. Note 857 (1942).

[4] C. E. Work and T. J. Dolan, The influence of fluctuations in stress amplitude on the fatigue of metals (Part II), Ninth Progress Report, Office of Naval Research Contract N 6-ori-71-T.O. IV, Project N R 031-005 (University of Illinois, Sept. 1948).

[5] T. J. Dolan, R. E. Richart, Jr. and C. E. Work, The influence of fluctuations in stress amplitude on the fatigue of metals (Part I), Seventh Progress Report, Office of Naval Research Contract N 6-ori-71-T.O. IV, Project N R 031-005 (University of Illinois, July 1948).

[6] J. A. Bennett, A study of the damaging effect of fatigue stressing on X4130 steel, Proc. Am. Soc. Testing Mat. **46,** 693 to 711 (1946); also J. Research NBS **37,** 123 (1946) RP 1733.

[7] F. E. Richart, Jr. and N. M. Newmark, An hypothesis for the determination of accumulative damage in fatigue, Proc. Am. Soc. Testing Mat. **48,** pp. 767 to 800 (1948).

[8] H. W. Foster, A Method of detecting incipient fatigue failure, Proc. Soc. Exp. Stress Anal. IV **[II]**, 25 (1947).

[9] ASTM Manual on presentation of data, Am. Soc. Testing Mat. (Philadelphia, Pa., 1947).

VIII. Appendix

1. Correction for Premature Failures

The proportion of premature failures for the four conditions in which they occur are

Stress amplitude	Cycle ratio or number of cycles	Premature failures
lb/in.^{2}		*Percent*
17,000	2x10^7	14
22,500	54%	14
22,500	98%	40
32,500	75%	7

For the first, second, and fourth conditions listed, the data were corrected for the premature failures by considering that these specimens had a value of $N_F=0$ at the test stress. As the values were actually less than zero, this assumption had the effect of making the average N_F at the test stress too high. However, for the conditions mentioned, where the proportion of premature fractures was small, this error was not considered significant.

For the third condition in this tabulation, the proportion of premature failures was so large that the method used in handling the data for the other three conditions was not considered satisfactory. Accordingly, a new value of cycle ratio was determined from the following considerations; as 40 percent of the specimens broke before the prestress was completed, those that were tested might be considered to be the strongest 60 percent of the population, and the average N_c^* for this portion is larger than that of the whole population. This new value, N_c, was determined by interpolation between the values for the top 60 percent of the specimens tested at ±25,000 and ±20,000 lb/in.^{2} (upper line on fig. 8). On this basis the cycle ratio of the specimens tested was 80 percent.

WASHINGTON, March 27, 1950.